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# THE DESIGN AND DEVELOPMENT OF A NIRS CAP FOR BRAIN ACTIVITY MONITORING

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ÉCOLE POLYTECHNIQUE DE MONTRÉAL

MÉMOIRE PRÉSENTÉ EN VUE DE L'OBTENTION

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présenté par : KASSAB Amal

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a été dûment accepté par le jury d'examen constitué de :

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# DEDICATION

*To All my teachers,*

*Especially those that I don't remember*

*May your light be forever glowing in me*

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Special thanks go to Dr. Sawan for his continued support during this particularly challenging project. It has been surprisingly rich and diverse journey with many new findings that unfolded throughout the course of its development. The complexity lurking behind simple concepts and manufacturing challenges have been particularly enriching and enlightening. Dr. Sawan's encouragement to continuously do more in order to unearth as much material as possible has been the main drive for these achievements.

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Finally, I would like to thank my family for their patience, and my parents for their support, during this turbulent ride of scientific research. I hope I will always be able to make you proud and always meet your expectations.

# RÉSUMÉ

Ce mémoire de maitrise est consacrée à l'étude de casques dédiés aux systèmes d'imagerie clinique basés sur la spectroscopie proche infrarouge (SPIR) et leur rôle en portant cette technologie d'imagerie dans son objectif désigné comme un dispositif d'imagerie portable qui peut être utilisé avec des sujets mobiles. En tant qu'une composante non-électronique, les casques SPIR ont été la plupart du temps à l'écart des études, cependant, avec l'émergence de systèmes portables sur le marché, le rôle de tels casques devient essentiel, voire le chemin critique, pour stabiliser les optodes intégrés dans ces casques.

Dans le cadre d'un projet multidisciplinaire de l'équipe Imaginc visant à mettre en oeuvre un dispositif d'imagerie multimodale EEG/SPIR portable, le travail présenté dans ce mémoire a été fait pour répondre aux exigences de plusieurs applications cliniques. Par conséquent, un casque dédié a été identifié permettant de maintenir le contact optodes/cuir chevelu quelle que soit la tâche demandée; En outre, le confort du patient est essentiel particulièrement pour le processus d'installation et pour les séances d'imagerie plus longues.

Afin de répondre à ces préoccupations, ce mémoire a porté sur le développement de plusieurs modèles de casques qui sont actuellement utilisés dans les prototypes EEG/SPIR complétés. Cela nous a permis de réaliser la première étude comparative entre les modèles fonctionnels dans différentes conditions distinctes: statique, mouvement de la tête et de la marche. De plus, une méthode de calibration de contact des optodes a été proposée par l'identification de la pression exercée par le contact sur la tête. La pression mesurée permet de maintenir le contact du cuir chevelu/optode requise. Aussi, nous avons proposé un outil pour faire écarter les cheveux du contact optodes avec la tête. Ces dernières conceptions apporteront des solutions appropriées afin de mettre en oeuvre le casque d'enregistrement multimodal tant attendu. Le développement futur, basé sur des concepts de pinces robotiques de casques SPIR, présente un bon potentiel pour introduire des solutions d'installation efficace des optodes..

# ABSTRACT

This master thesis is dedicated to the study of near-infrared spectroscopy (NIRS) caps and their role in bringing this imaging technology into its designated goal as a clinical imaging device that can be used with freely moving subjects. As a non-electronic component, NIRS caps have been mostly left out of studies, however, with the emergence of portable NIRS systems into the market, the role of NIRS caps is becoming an integral part as an optode stabilization method.

As a part of a multidisciplinary project of the Imaginc group aiming to create a multimodal portable EEG/NIRS imaging device, the work presented herein was made to accommodate the requirements of several clinical applications. Thus, an ideal cap was identified as a design capable of maintaining optode/scalp contact regardless of the required task; moreover, patient comfort is essential specially for longer imaging sessions.

In order to address these concerns, the thesis focused on adapting and developing several models that are currently being used in NIRS and EEG systems into our current Imaginc device. This allowed us to perform the first comparative study between the working models in various distinct conditions: static, moving the head and walking. Moreover, a method to calibrate the optode contact was suggested by identifying cap contact pressure on the head and defining the pressure required to maintain good scalp/optode contact in addition to the pressure comfort margin on the head. Also, the design of hair-clearing sockets was presented, which is the first step towards creating a system than can be used by a single person, and reducing the time needed for NIRS system installation. This study concludes by possible future development of NIRS caps based on robotic gripper concepts which may create systems that can provide good optode stability and user comfort.

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| | |
|---|---|
| APD | Avalanche photodiode |
| BCI | Brain computer interface |
| CW | Continuous wave |
| DOI | Diffuse optical imaging |
| DPF | Differential pathlength factor |
| EEG | Electroencephalography |
| FD | Frequency domain |
| fMRI | Functional magnetic resonance imaging |
| HbO | Oxyhemoglobin |
| HbR | Deoxyhemoglobin |
| LD | Laser diode |
| LED | Light emitting diode |
| MRI | Magnetic resonance imaging |
| NIR | Near infrared |
| NIRS | Near infrared spectroscopy |
| PET | positron emission tomography |
| SNR | signal-to-noise ratio |
| TD | Time domain |

# LIST OF APPENDICES

# INTRODUCTION

There are several reasons to call this age the "brain age" as science is finally starting to make great leaps in deciphering how the human brain functions thanks to the multitude of imaging modalities available today. However, in order to fully understand the human brain in normal conditions, with the multitude of discernible (walking, talking and hearing) and indiscernible functions (thinking, dreaming and imagining) that take place simultaneously during the course of the day, longer imaging under these conditions will have to be conducted. Over the past decades, attempts to isolate certain cognitive functions, through controlled and short sessions of brain activity imaging, has been the main method for deciphering the human brain (Cui et al., 2011; Cutini et al., 2012; Villringer et al., 1993). However, a more comprehensive look at brain functionality in daily life is a necessary step towards bringing forth the next generation of bionic and brain-computer interface (BCI) achievements, such as electroencephalography (EEG) and near infra-red spectroscopy (NIRS)-controlled wheelchairs (K. Choi & Cichocki, 2008; Craig & Nguyen, 2007; Rebsamen et al., 2006; Tanaka et al., 2005), robotic limbs (Aasted et al., 2011; Shoureshi et al., 2010) and other thought-controlled electronic devices (Tsubone et al., 2007). From a medical standpoint, extended brain imaging sessions are also necessary in neuroscientific research to monitor patients suffering from certain illnesses such as schizophrenia (Fallgatter & Strik, 2000; Suto et al., 2004) or for locating the source of seizures in epilepsy (Gallagher et al., 2008; Machado et al., 2011; Wallois et al., 2010).

Such needs have given rise to portable brain imaging techniques, such as EEG, and NIRS. In addition to portability and non-invasiveness which allow them to be used with children and infants (Aslin & Mehler, 2005), these techniques are also relatively not expensive, portable and offer a higher temporal resolution than traditional immobile techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) (Lloyd-Fox et al., 2010). This is essential in identifying transient activation areas in the cortex and registering the onset of brain activation in response to a certain stimuli. In general, the higher temporal-resolution comes at the expense of spatial-resolution. However, the biggest deficiency of EEG and NIRS is penetration depth or depth resolution, while EEG only captures electrical signal variations on the scalp, NIRS offers 1-2 cm depth resolution that is very suitable for capturing cortical activation (Huppert et al., 2009) however it cannot be used in detecting deeper brain functions.

The possibility of long-term cortex activity monitoring is still extremely important and has a lot of real life applications today (Belda-Lois et al., 2011; Nagaoka et al., 2010; Watanabe et al., 2002; Zhang et al., 2010), which creates a ready demand for these portable brain imaging systems. But while EEG signals are inherently noisy and nonlinear (Hoshi, 2007), other challenges still affect the long-term portability of NIRS systems, mainly: NIRS optode stability and patient comfort. These two concepts are completely dependent on the actual brain-device interface, the NIRS monitoring cap itself, where no current solutions has successfully addressed the long-term portability of the device.

The objective of this thesis is to address such issues as optode stability for portable NIRS systems with freely moving subjects, in addition to tackling patient comfort and easy NIRS cap installation. This is done by the following criteria:

1. Evaluating and optimizing present caps and optode stabilizing methods in order to assess their short-term as well as long-term portability.
2. Introducing a NIRS cap quantification method that can be used to categorize NIRS caps with regards to their portability based on the amount of pressure they induce on the head. This is done by identifying the two pressure limits necessary: the minimum pressure necessary to stabilize the optode, versus the maximum comfort pressure threshold on the head.
3. Introducing methods that allow for easier NIRS cap installation
4. Addressing possible solutions for long-term monitoring caps

The work presented in this thesis is based on the collaborative work with the Imaginc group in order to create a portable EEB/NIRS brain imaging system. The rigorous testing and feedback from various members was an essential part of the results obtained. The diversity and multidisciplinary nature of the group has provided a nice background to test the caps under various working conditions.

This master thesis consists of five chapters. The first chapter sets the scientific background related to the project, it introduces the basic principles of NIRS imaging in addition to analyzing the various components of a NIRS device in order to establish the exact role of a NIRS cap and whether future electronic developments can compensate for the need of such an optode stabilizing methods. It also identifies the major challenges in creating a NIRS cap, such as head shape variations and the need to maintain continuous pressure throughout the imaged surface.

Chapter 2 offers an extended review of commercially available NIRS cap solutions today, in addition to previous studies that incorporate NIRS cap designs. After discussing and evaluating these solutions, the concept of a "perfect grip" is introduced by drawing a parallel between the requirements of a NIRS cap and that of robotic grippers.

Chapter 3 outlines the different cap designs that were made throughout the duration of the project, listing their manufacturing methods, advantages and disadvantages and the applications that they are employed in presently. It also demonstrate hair clearing methods that were developed for easier cap installation.

Chapter 4 quantifies for the first time the parameters associated with optode stability and headwear comfort, by identifying the pressure value associated with each case. In this chapter also, the first comparative study is presented between various NIRS cap solutions with regards to stability and comfort, by comparing NIRS signal fluctuations associated with movement of the head, or the body versus the control state that is static, using each cap design.

Future NIRS cap solutions are presented in Chapter 5, based on comparable studies in the field of robotics and grippers. One particular solution, the vacuum cap design was investigated in detail in order to establish its feasibility, properties and requirements.

Finally, a conclusion section is presented outlining the major contributions and future work that can be done in order to realize better long-term brain activity monitoring systems.

# CHAPTER 1

# SCIENTIFIC BACKGROUND

In order to pinpoint the exact role of NIRS caps in present as well as future applications, basic concepts of NIRS technology need to be identified in order to differentiate between issues that can be resolved by using more advanced electronic solutions, versus inherent physical limitations that has to be compensated for using an accessory that compliments the system. In addition, the NIRS device installation process will be reviewed as a secondary objective, which is generally proportional to the amount and type of hair present in the imaged area. Although in retrospect, the installation process itself is more significant for short-term monitoring applications.

## 1.1 NIRS Principles and Instrumentation

NIRS is based on the relative transparency of human tissue to near infra-red light (650nm-950nm wavelength) which allows it to penetrate the skin, subcutaneous fat, skull and brain. This was demonstrated as early as 1977 by (Jobsis, 1977). While the main mechanism of near infra-red (NIR) light propagation in biological tissue is scattering, attenuation of NIR light is mainly due to absorption by pigmented compounds (chromophores). In general, high attenuation of NIR light is due to hemoglobin, which has a distinctive absorption spectrum based on its oxygenation levels. The difference in the absorption coefficient between oxy and deoxy hemoglobin, shown in Figure 1-1, is what allows NIRS to record their variation over time by using two different light-waves specific for each hemoglobin type (Lloyd-Fox et al., 2010; Sato et al., 2006). However, other light attenuation sources include chromophores of skin and hair melanine (Marco Ferrari et al., 2004). These are usually regarded as constant, and their absorption level is compensated for by adjusting the light intensity.

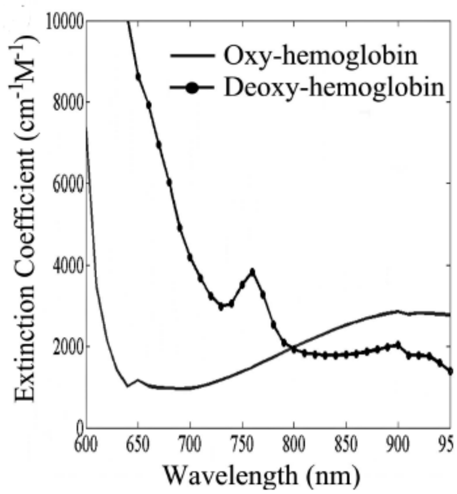



Figure 1-1: Light absorption spectrum of oxy and deoxy-hemoglobin, the span between 650 and 950 nm is called the "optical window" due to the relatively low absorption factors in tissue (Huppert et al., 2009)

In general, the arterioles irrigating the neurons are very small making absorption spectrum changes due to a single neuron activation undetectable; however neurons are spatially clustered and form "cortical columns" that share similar functional properties and information-processing modules in the cortex. Thus the cluster formation of neurons responding simultaneously to a certain action is what makes the changes in brain oxygenation detectable using optical imaging techniques (Vanzetta & Grinvald, 2008). During cortical activation the increase in Oxy-hemoglobin (HbO) and simultaneous decrease in Deoxy-hemoglobin (HbR), or what is known as neurovascular coupling (Figley & Stroman, 2011; Vanzetta & Grinvald, 2008) can be recorded using NIRS devices, thus registering activated cortical zones in response to a certain stimuli or action. In other words, NIRS allows the detection of neuronal activity indirectly by measuring changes in blood oxygenation levels and blood flow (Delpy & Cope, 1997; Rolfe, 2000; Strangman et al., 2002)..

A lesser known prospect of NIRS is the possibility of using optical imaging in non-hemoglobin based measurements, by recording data from several wavelengths simultaneously which allows the detection of tissue chromophores, including cytochrome oxidase, which is a marker of metabolic demands (Heekeren et al., 1999). Other studies suggest the possibility of identifying cell swelling that follows neuronal firing, suggesting a direct detection of neuronal activity using optical imaging instead of the inferred detection of such activity via neurovascular coupling, however this type of signals are 0.01% smaller than hemodynamic ones, which makes them less reliable using current NIRS techniques (Gratton & Fabiani, 2001; Steinbrink et al., 2000; Strangman et al., 2002).

An example of a portable NIRS system is shown in Figure 1-2. A typical portable NIRS device is comprised of three major components: 1) A brain-device interface which includes the optodes and the cap used to stabilize them; 2) the electronic control module which defines the illumination scheme and collects the returning data from the detectors; and 3) the software that analyses the data using signal processing algorithms and presents the results in a user friendly interface while providing control over the system in general. In order to successfully assess NIRS development possibilities the entire system has to be examined.


Figure 1-2: Combined EEG/NIRS portable system developed by the Imaginc group of Polytechnique Montreal. The brain device interface represents the combination of optodes and the helmet used to stabilize them, these are wired to the control module that can be fixed on the belt. Data collected in the control module are transmitted via Bluetooth transmission to a laptop where signal processing takes place in real time

### 1.1.1 The brain-device interface

NIRS signals are gathered using optodes that consist of a near-infrared light (NIR) emitting source and a light detector. The source shines light directly into the scalp, which is scattered by head tissue causing it to deflect in all directions. A small fraction of this light, one out of $10^9$ photons, resurfaces back to the scalp 3 cm (typical distance) away from the entry position (Huppert et al., 2009) (based on the age, curvature and size of the head) and is captured by the detector. The change in the amount of detected light overtime is used as an indicator of the absorption variation of NIR light due to cortical activation. Thus the NIRS signal, unlike that of EEG, relies on this source-detector coupling, or "channel", and on the assumption that light intensity entering the scalp is constant as well as the conditions affecting optode light emission and detection throughout the imaging process. Practically, there are various factors that affect this source-detector coupling, such as small displacements of optode caused by instability and movement artifacts. Additionally, minor inclinations of the optodes that may fluctuate with movement can cause the optode to detach partially or completely from the scalp leading to detection of surface light that is not reflected back from the head (in case of detector inclination), hair quantity differences in front of the optode which translates into variation in light absorption by hair melanin in addition to disparity in light intensity entering the scalp (in case of emitter inclination). This emitter-detector dual relationship is the main reason why NIRS systems are much more sensitive for movement artifacts and optode instability compared to EEG.

As mentioned previously, optical penetration-depth is usually half the source-detector distance which is typically 3 cm. The approximately 1.5 cm penetration depth translates to 5-10 mm of outer brain tissue penetration after subtracting the thickness of the skin, subcutaneous fat and skull, which allows the detection of the outermost cortex activation (Marco Ferrari et al., 2004; Huppert et al., 2009). The scattered light path-length inside the head is longer than the physical distance between the source and detector, this NIR light distribution was simulated by Okada demonstrating that light diffuses in all directions in the scalp, skull and cerebrospinal fluid, but the sensitivity of each source-detector pair exhibits a banana shaped profile with two narrow ends at the source-detector locations (Okada & Delpy, 2003).

NIRS allows the detection of both HbO and HbR changes by using two wavelengths of light simultaneously, this is essential because the absorption coefficient of the two species are roughly in the same order of magnitude and a single wavelength measurement will not be able to distinguish between the two. On the other hand, three wavelengths are used in some cases in order to either extract changes in other species, such as water, or coupled with time resolved methods additional parameters such as blood flow and absolute tissue saturation can be calculated (Strangman et al., 2002). There are various types of NIR light sources, the two most commonly used emitters today are laser diodes and light-emitting diodes (LEDs). Laser diodes provide technical advantage over LEDs due to their higher light-intensity and small optode size, which allows for better hair penetration and scalp contact. However, for portable long-term systems they are not considered as a practical option owing to their high energy-consumption and cost. Therefore, portable NIRS devices rely on LEDs that require generally a simpler circuitry and generate a light spectrum of about 30nm (Strangman et al., 2002).

As for light detectors, only avalanche photodiodes (APDs) combine low power-consumption with the capacity to increase the detected light intensity, since they translate the amount of detected photons into current. APDs are fast with more than 100 MHz speed and high sensitivity with approximately 60 dB dynamic range. This is more advantageous than silicon photodiodes that have a medium speed and low sensitivity but offer a higher dynamic range of approximately 100 dB (Strangman et al., 2002). There are a lot of efforts today to create new LED and APD designs with enhanced capabilities and smaller size using modern microfabrication methods, which is an essential part in developing better portable NIRS systems.

Optodes are stabilized on the scalp using different methods, either a cap (soft headwear), a helmet (rigid headwear) or patches that are fixed on the head using supplementary attachments to the chin or to a belt under the arms. The primary objective of these stabilizing techniques is to enforce as much optode stability as possible for the imaging duration, which becomes a particularly challenging task with the amount of freedom the person is allowed during the session. However, this topic has been generally left out of discussion in most NIRS research articles with some exceptions (Huppert et al., 2009; Kiguchi et al., 2012; Piper et al., 2014). The following sections offer a more comprehensive look at the subject, which is also the focus of this study.

### 1.1.2 The electronic control module:

The electronic control module offers a means of distinguishing between the signals gathered by the detectors, especially when there are various light emitting sources. This requires either multiplexing and/or modulating the sources and then decoding the detected signal in order to identify the source of each returning signal. There are various multiplexing or time-sharing schemes (Siegel et al., 1999), in addition to time division-multiplexing or frequency modulation (D. A. Boas et al., 2001).

NIRS techniques available nowadays can be summarized into three groups based on the type of illumination used, as illustrated in Figure 1-3. The first and most common type is Continuous-

Wave (CW) illumination which simply measures the backscattered light intensity attenuation. While, frequency-Domain (FD) uses intensity-modulated light in order to measure both attenuation and phase delay of returning light. The third technique is the Time-Domain (TD) which relies on a short pulses of light as an illumination source, and detects the shape of the pulse after propagation through the tissue, this provides information about tissue absorption and scattering as well as spatial specificity (Strangman et al., 2002).

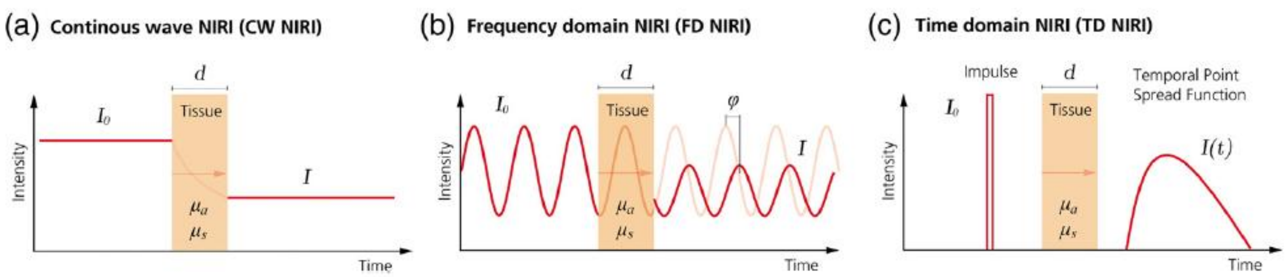



Figure 1-3: The three types of NIRS imaging techniques (Felix Scholkmann et al., 2014)

CW technique provides real-time data on changes in HbO and HbR compared to an initial value, the baseline, which is defined as the "zero" state and is relatively simple and cost effective. However, only the FD and TD methods can provide absolute characterization of optical tissue properties and values, including accurate separation of absorption and scattering in tissue. The preference of CW systems over FD and TD is primarily due to the fact that absolute quantification is not necessarily important in all neuroscience applications, rather the detection of change in brain activity (Marco Ferrari & Quaresima, 2012). On the other hand time-resolved systems have a lower time-resolution and are more susceptible to noise and movement artifact since determining time of flight is highly affected with geometrical and contact changes, which makes these systems unsuitable for small signals detection or with freely moving subjects (F Scholkmann et al., 2010). The differences between the three systems are summarized in Table 1-1. Most commercially available NIRS devices offer CW systems with only one FD-based system, Imagent from ISS, this non-portable device relies on laser diodes emitting at two wavelengths, 690 nm and 830 nm, with a sampling rate of ~6 Hz in normal conditions, and up to 50 Hz when using only one wavelength ("ISS Focus and Discover," 2014).

Future developments of FD and TD technologies may introduce new systems capable of imaging and quantifying NIR signals for portable devices, especially with the great leaps accomplished in microfabrication methods. However, the creation of a stable interface remains a major challenge even with expectations of a better and more advanced electronic components.

Table 1-1: Main differences between the three NIRS techniques
(Adopted from Ferrari et al, 2012)

| **Main Characteristics** | **Continuous wave** | **Frequency Domain** | **Time Domain** |
|---|---|---|---|
| Sampling rate (Hz) | ≤ 100 | ≤ 50 | ≤ 10 |
| Discrimination between cerebral and extra cerebral tissue | Not possible | Feasible | Feasible |
| Measuring HbR, HbO | Only changes | Absolute value | Absolute value |
| Measuring scattering, absorption coefficient and pathlength | No | Yes | Yes |
| Measuring tissue HbO saturation (%) | No | Yes | Yes |

For portable and wireless devices the most important aspects in evaluating various NIRS components and operation systems is usually power efficiency and compactness, in order to create a system that can fit either on the belt or inside a backpack that the participant can carry for up to few hours. The control module as well as the brain-device interface represent the portable portion of the system due to the direct relationship between the optodes and the control center. However, future designs may be able to either detach or integrate this component from the optodes and join some of its components with the data analysis and user interface unit (the computer). This shift in the design concept not only allows for more complicated and sophisticated illumination techniques (such as FD and TD) to be used with portable devices, it will also result in a lighter and more accommodating imaging device by creating a wireless data/control transmission free from the encumbrance of optode  connecting wires.

### 1.1.3 Data analysis and user interface

There are several theoretical models to quantify NIR measurements by assuming how light behaves in tissue, but the two most widely used approximations are the differential pathlength factor (DPF) and diffusion approximation. Both assume that tissue is homogeneous however, DPF assumes that change in light attenuation, including the ones caused geometrical or structural changes, reflect changes in chromophore concentration (Huppert et al., 2009). On the other hand the diffusion approximation assumes that scattering is much larger than absorption and that each type of tissue has a specific geometry (infinite, semi-infinite, slab or two-layered). While the PDF method is in agreement with the Boltzmann diffusion approximation, however the approximation method can be used to obtain absolute absorption and scattering coefficient values in tissue which is important to calculate chromophore concentrations (Wolf et al., 2007).

In general both computational models rely on quantification over a certain path, passing through scalp, skull, cerebral spinal fluid and reaching 5-8 mm of brain tissue. The thicknesses of these layers particularly the skull and cerebral spinal fluid vary interpersonally according to age and gender (Huppert et al., 2009), other factors that can also play an important role are melanin concentrations of hair and skin. These differences are bound to create biases in spatial localization of brain activity (Custo et al., 2006) and they are particularly important in absolute value measurements, such as in TD and FD methods. However, they are less significant in relative values provided by CW methods. Several studies have attempted to clarify these interpersonal differences using MRI or computerized tomography, particularly in order to determine how tissue absorption changes is translated into variations in detected light intensity (D. Boas et al., 2002; Gibson et al., 2005; Okada & Delpy, 2003). On the other hand, variation in these conditions during the imaging process such as changing quantities of hair melanin have no electronic solution so far, and can be reduced or eliminated by creating optodes that are in constant contact with the scalp at all times, after rigorous hair tossing procedure during installation. This is particularly challenging in long-term imaging applications with freely moving patients.

On the other hand, noise sources in NIRS can be characterized into three main groups: instrumental, experimental and physiological artifacts. Instrumental and experimental errors include movement artifacts in addition to any hardware or software malfunction and are not linked with the physiological changes measured. These signals have to be removed prior to data analysis, otherwise they may propagate after data treatment and overpower the measured signals (Huppert et al., 2009). While some movement artifacts can be filtered out using additional data collecting methods such as a camera (Bang et al., 2013) or an accelerometer (Iramina et al., 2010; Virtanen et al., 2011), other movement artifacts that are related to optode displacement or detachment from the scalp are harder to detect and there are no present solutions for this issue. On the other hand, physiological changes due to hemoglobin fluctuations, which may be due to blood pressure or heartbeat variations are usually treated with filters after the conversion of raw signals to hemoglobin units (Huppert et al., 2009), or by using additional channels to measure extracortical hemodynamic variations (Gagnon et al., 2014)

## 1.2 The Importance of NIRS Caps

### 1.2.1 Continuous optode contact with the scalp

Due to the interesting work published recently by Yücel et al., it is possible today to accurately assess the importance of having a completely stabilized optode on NIRS imaging data (Yücel et al., 2014; Yücel et al., 2013). In their study, the authors stabilized fiber optic optodes on the scalp using collodion, which is a standard procedure in monitoring epilepsy patients using EEG. Patients were monitored for several days in the hospital and the authors reported 90% reduction in signal change due to movement artifacts, an SNR increase by 6 and 3 folds at 690 and 830 nm wavelengths, respectively, and a statistically lower change in both HbO and HbR during movement artifacts (Yücel et al., 2013). Unfortunately, this type of stabilization methods cannot be used with portable systems as collodion is restricted for hospital use; in addition, the size of portable NIRS optodes is larger than fiber optics used with non-portable NIRS systems.

Therefore, for portable systems that are meant for use in normal settings, it is obvious that optodes have to be in contact with the scalp throughout the monitoring session. This is essential not only to direct NIR light into the scalp, but also in order to prevent any hair from covering or moving in front of the optodes during the monitoring session which may affect the results by introducing false light attenuation values. Moreover, stretchable caps may introduce a small variation in optode distance, especially during normal head movements which may cause the optodes to shift positions or incline into different angles thus affecting the light path-length. Therefore, either the distance between source and detector has to be fixed at all times, which requires non-stretchable material, or an electronic grid based on miniature strain gauges and contact sensors need to be introduced in order to provide additional information pertaining to dynamic optode position changes, which is a challenging and complicated solution. Several current NIRS optodes come equipped with built in springs in order to ensure scalp contact by providing additional force at the exact optode location, which is generally useful with freely moving subjects.

In general, it is evident that the need to achieve a completely stable optode configuration throughout the imaging process may not be resolved with foreseeable software or electronic advances, making it a clear objective for NIRS cap design.

### 1.2.2 Easier installation

Nowadays NIRS has proven to be very effective and reliable in research conducted on large groups of subjects, with low reliability still in single subjects (Kono et al., 2007; Plichta et al., 2007; Plichta et al., 2006; Schecklmann et al., 2008). Possible reasons for lack of reliability are superficial tissue, or systemic physiological changes in addition to possible instrumental artifacts and noise. Although this fact is expected to change with better understanding of brain functionality and constant development of NIRS systems. However, presently most research is focused on group evaluation which is generally very taxing given the complexity of the installation process that may take up to 1 hour depending on the type of hair and the head area covered in each study. Imaging sessions that require partial head coverage for specific zones are generally easier to carry out which allows for an average of 2-3 patients tested per day, while complete monitoring of the brain with full head coverage may take up to 4-5 hours for a normal session, thus testing would be limited to one patient per day. It has to be mentioned that this fact becomes less significant for long term brain activity monitoring as patients may be expected to wear the device for periods extending from 6 to 12 hours, with hopes for achieving EEG comparable monitoring sessions that can be extended for days or even a week.

However, given the importance of this procedure for NIRS cap designs, details of the installation process with particular inter-subject difficulties will be discussed in detail in the following section.

### 1.2.3 Patient comfort versus optode stability

Stability of optodes in their set positions is a challenge even for traditional NIRS devices. Presently all NIRS systems rely on applied pressure of one form or the other (straps, springs or additional attachments) to ensure that optodes remain stable even with simple and short term tests such as finger tapping. Normally, more stability is achieved by increased pressure on the head, which comes at the expense of patient comfort and presents the main challenge for long term monitoring plans. Additionally, pressure itself is not a guarantee for a stable optode design since it often leads to sliding of the cap, that may be due to patient agitation, and requires additional straps to hold it in place. When it comes to carefully examining localized pressure induced on the head by NIRS caps several variables need to be accounted for, the most important of which are variations of head sizes and shapes between people who share the same head perimeter (Ball et al., 2010).

As mentioned previously, the primary goal of applied pressure is to stabilize optode positions relative to each other and maintain scalp contact since movement artifacts resulting from linear or angular acceleration can be filtered out using electronic components, such as an accelerometer (Iramina et al., 2010; Kim et al., 2011; Virtanen et al., 2011). However, there are no present data analysis and filtration methods to account for changes in relative optode positions or transient scalp contact errors. On the other hand, no studies identifying comfortable pressure margins on the head have been published, which is important in order to establish a guideline recognizing localized pressure values that are uncomfortable.

Additional straps and optode wires present another source of discomfort, particularly since they tend to confine the movement of the person wearing the device. While the effect of increased pressure due to NIRS caps on cranial blood circulation does not seem to be a major concern.

Since optode size and connecting wires have an important affect on the stability and comfort of the system, future electronic solutions for long-term brain activity monitoring may be developed into wireless optode designs, with smaller optodes that are easier to stabilize and can penetrate the hair to establish scalp contact more readily. In these designs, data control/transmission can be either designed individually in each optode, or become integrated as a flexible circuit into the cap itself. However, although this possible electronic development may reduce movement artifacts and offer better portability and comfort, the pressure margin separating patient comfort from optode stability has to be identified in order to be able to create a better interface.

## 1.3 Cap Installation Process

The cap installation process starts with basic measurements of the head, in order to determine the location of some of the important reference positions according to the 10/20 international positioning system shown in Figure 1-4. Although this method was originally developed for EEG electrode location distribution, however it has proven to be very successful to ensure standardization and reproducibility of neurological studies. This requires the measurement of the participant's head front to back from the Nasion to the Inion, then the locations are identified as 10% or 20% of this total distance. However, unlike EEG, NIRS optodes cannot follow the exact 10/20 system positions, since the distance between the optodes have to be confined to a 3 ±0.5 cm. Therefore only one or two of the key locations are identified and are coupled with the location of one optode position on each side of the head.

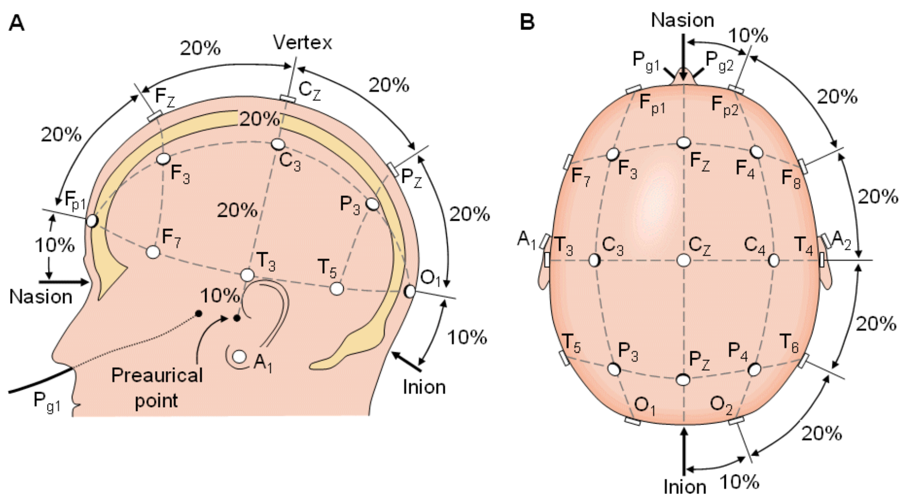



Figure 1-4: The international 10/20 system

This is followed by a mapping process for the position of the other optodes, using a 3D locator connected to the NIRS software. In certain studies this kind of rigorous identification of position may not be required, if the comfort of patients being monitored is of a particular concern (in the case of children for example) or if the area being mapped covers a well known anatomical part, such as the entire prefrontal cortex. It is however extremely important to map the optode positions on the cap beforehand in order to calculate the path-length of each channel.

The cap is then stabilized tightly on the head, using either chin straps or Velcro bands. This is important since the following procedure which is tossing the hair in every optode position requires a tight fit cap that is able to hold the displaced hair in place so that it will not return to its natural position. Once hair in the pre-designated optode position are tossed the optodes are placed directly afterwards. Tossing the hair is the most time consuming process in this procedure, and the stability of the cap as well as the quality of the signal rely heavily on the hair type of the person wearing the cap. Dense hair may act like a spring adding an extra force that pushes the cap outward or causes it to slide in response to the pressure that is created by the cap.

While dark colored hair would require extra attention in clearing, since the quantity of melanin will invariably affects the light intensity detected, especially in locations that lack scalp contact which may introduce moving hair strips causing light absorption variations. The affect of hair type is indeed very significant on a successful NIRS session, therefore it is highly recommended to note the type and hair color of participants in NIRS studies and the percentage of failed experiments in relation with hair type, which may give a clear indication to the effect it has on NIRS imaging.

Based on the degree of freedom the patient is allowed during the monitoring sessions, additional straps may be added on top of the optode in order to stabilize them and secure them in place, followed by a dark cover in order to shield from ambient light.

## 1.4 Head Shape Variations

Head sizes are categorized into three major ranges: small, medium and large; however, different head shapes within the same size makes global headwear designs for a tight fit system on all cranial zones a very challenging task. For example the comparative study presented by Ball et al. between Caucasian and Chinese heads shows that Chinese heads are rounder with a flatter back and forehead, as shown in Figure 1-5 (Ball et al., 2010).

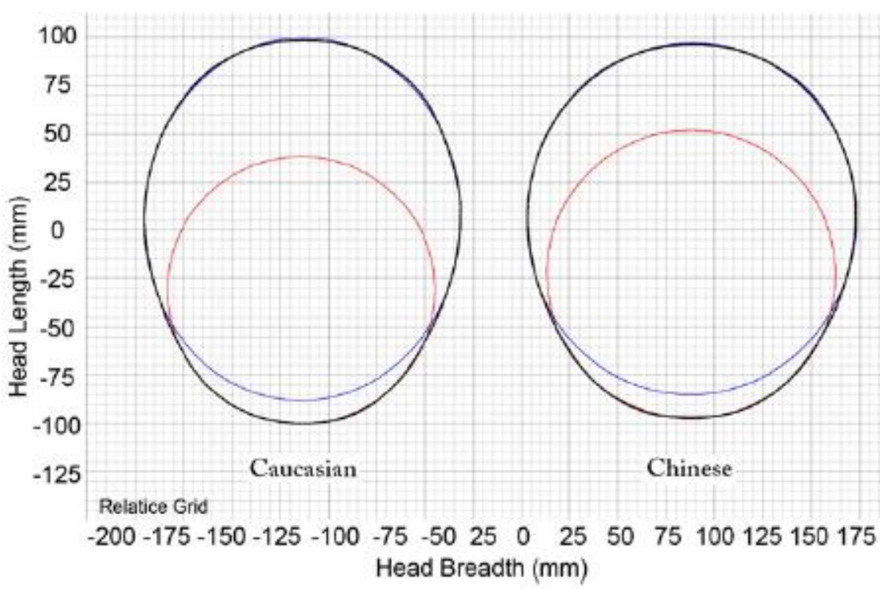



Figure 1-5: A model with an ellipse and a circle fitted to the mean contours of Chinese and Caucasian heads (Ball et al., 2010)

These variations create different set of features for cap designs whether the material used is stretchable or rigid. Increased pressure on the cap using stretchable material will tend to expand the fabric over flatter areas creating zones that lack contact with the scalp. In contrast rigid material used primarily as head patches to cover certain areas of the head are more difficult to bend and curve around in order to ensure contact at all areas.

Therefore, commonly used techniques for securing the cap, causes high localized pressure on certain areas, while other areas have no pressure and lack contact with the scalp.

## 1.5 Identification of NIRS Cap Objectives

Based on the previous analysis of the NIRS electronic system and its limitations, a successful long-term NIRS monitoring cap has to be capable of achieving the following conditions:

- Maintain optode scalp contact at all locations regardless of the variation of head shape.
- Ability to either monitor the pressure values induced by the cap on various locations, or to alternatively offer a new stabilizing means for the optodes that rely primarily on equally distributed pressure instead of localized one.
- Easy installation

These conditions are independent of the type of NIRS technique used and while electronic developments may enhance the portability of future NIRS devices by creating smaller, wireless optodes for example; the need for a mechanical stabilization method cannot be compensated for by foreseeable future electronic developments. The only possible alternative for having such a support system is by using smaller optodes that can be glued to the scalp with collodion for several days of continuous monitoring. This has been reported using fiber optics in hospital settings (Yücel et al., 2014; Yücel et al., 2013), however it cannot be considered as a viable solution for regular use in normal settings.

On the other hand, future electronics may find a way to alleviate the need for the lengthy and time consuming installation process by minimizing the optode surface area in order to allow it to penetrate the hair and establish contact with the scalp. Therefore future NIRS cap designs may have integrated optodes with only two objectives to fulfill, optode stability and patient comfort.

# CHAPTER 2

# LITERATURE REVIEW

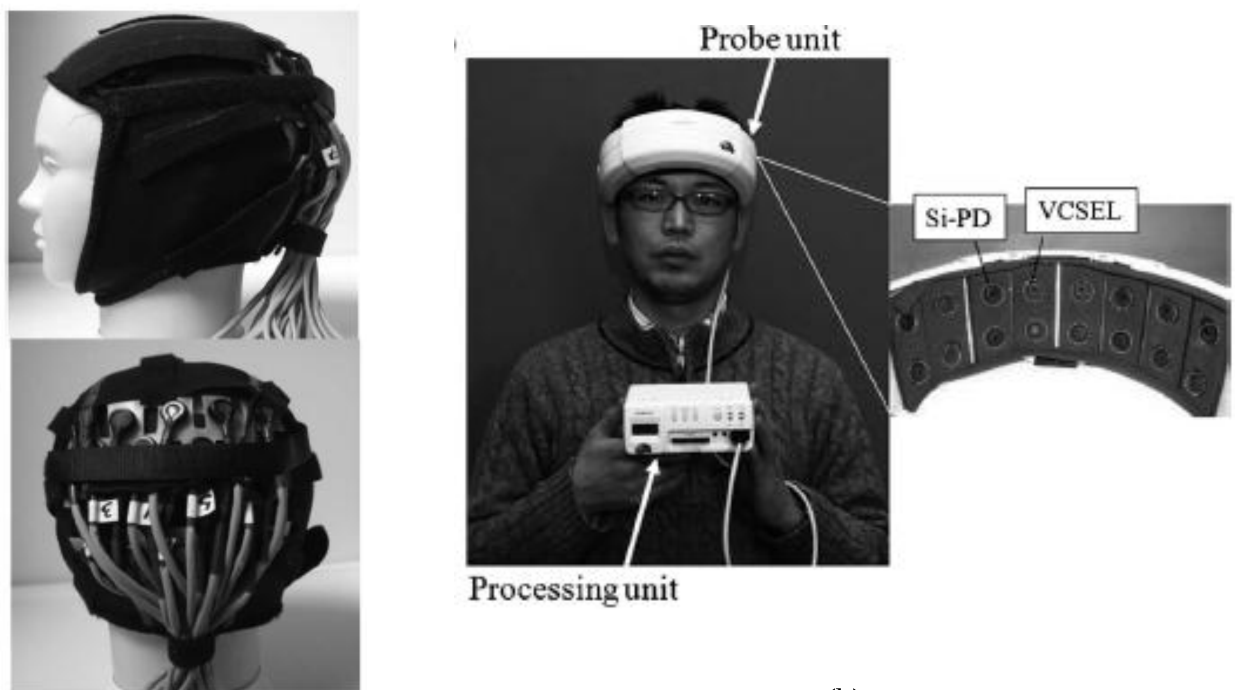
There is an abundant of research and review papers documenting almost every single aspect of NIRS technology, not to mention the countless papers that are being published every day on various topics of NIRS applications and development. These reviews are a tribute summarizing and presenting this very interesting field in all its details. Starting with the history of NIRS imaging (Marco Ferrari & Quaresima, 2012), NIRS instrumentation and methodology (M Ferrari et al., 1993; Felix Scholkmann et al., 2014; Torricelli et al., 2014), progress of NIRS topography in clinical applications (Cabeza & Nyberg, 2000; Lin et al., 2009; Pereira et al., 2007; Sakatani, 2012; Wolf et al., 2007; Zheng et al., 2013), the principles and limitations of NIRS (Marco Ferrari et al., 2004), analysis methods (Huppert et al., 2009) in addition to the other reviews pertaining to clinical applications of NIRS technology (Hoshi, 2003; Leff et al., 2011; Obrig & Villringer, 2003) to name only few.

On the other hand, although developments in miniaturized probe arrays and portable instruments have been reported for over ten years (Atsumori et al., 2007; Bozkurt et al., 2005; Hoshi & Chen, 2002; Muehlemann et al., 2008; Sagara et al., 2009; Yurtsever et al., 2003), these devices were only dedicated to a specific portion of the head (mostly the forehead) and come at the cost of a low number of channels, as shown in Figure 2-1. On the other hand, thus far there are only limited amount of studies dedicated to NIRS cap designs, none of them however consider their long-term or short-term portability with freely moving subjects, although this is expected to change shortly due to the great advancements made in the field.

Figure 2-1: Example of a Wireless NIRS device (Hoshi & Chen, 2002)

## 2.1 NIRS caps in literature

The important role of NIRS caps and the installation process in general, is presented only on rare occasions in few publications, such as the study presented by (Huppert et al., 2009), where the authors voiced the importance of stabilizing the optodes in order to reduce experimental errors. For this purpose the authors suggest anchoring the optical fibers to an additional location on the subject's body (such as a backpack) in order to reduce the effect of the weight on the motion instability created. They also caution from tightly wrapping the optodes on the subject's head by bandages due to the discomfort that would be caused by this additional restrains. This may very well be the first documentation of the sensitive balance required from NIRS caps between optode stability and patient comfort.



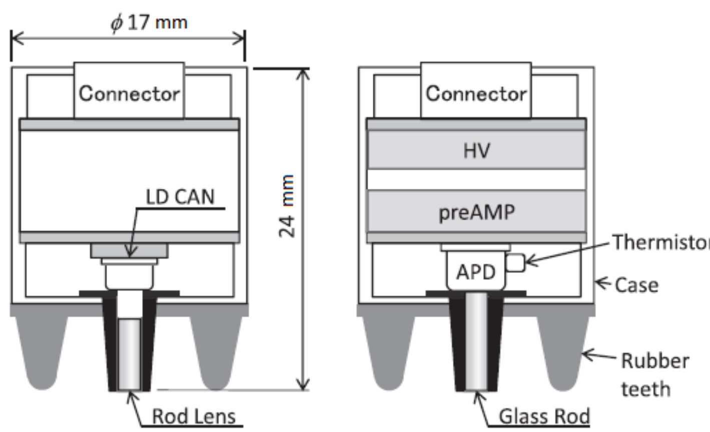

(a) (b)

Figure 2-2: Different NIRS cap solutions presented in research: a) Stretchable cap design with additional Velcro attachments to hold the optodes in place (Huppert et al., 2009), b) Prefrontal cortex head band for portable NIRS systems (Atsumori et al., 2009).

The cap design proposed by Huppert et al. (2009) is a stretchable cap that helps in stabilizing a polymer patch in place and is anchored by Velcro attachments as shown in Figure 2-2a. This solution relies on plastic embedded optodes that are affixed with Velcro, therefore removal of the hair has to be done indirectly from the sides. For moving patients the authors specify that more stability has to be enforced which requires a more rigorous processing of hair tossing and optode securing.

The earliest portable or wearable NIRS devices focused on non haired regions, such as the study by Atsumori et al. 2009. However, these solutions are limited to the prefrontal cortex and do not present a model that can be generalized to haired regions.

In contrast, the wearable NIRS system presented by Kiguchi et al. focused on a design for haired regions (Kiguchi et al., 2012). The cap was made of black rubber, with a special design for laser diodes (LD) and APD packaging in order to direct and guide the light into the scalp and the detectors. The design of the optode packaging is shown in Figure 2-3. Extreme care was dedicated to the optode design, that was accompanied with rubber teeth around the optode position in order to hold the hair in place and reduce the discomfort presented by the pressure of the spring loaded optode (Kiguchi et al., 2012).




(a) (b)

Figure 2-3: Wearable NIRS cap for haired region (Kiguchi et al., 2012): (a) A general look at the NIRS cap design (b) Emitter and detector encapsulation design showing the glass rod, and the surrounding rubber teeth to hold the hair in place and relieve the pressure

Although this study was dedicated to the demonstration of a wearable NIRS device designed for the haired regions, there is no mention in the study for the installation process, nor whether there was any attempt to remove or toss the hair in the areas beneath the optodes themselves. The shape of the cap may suggest that the authors have opted for the use of high intensity light via the LDs in order to compensate for any losses due to melanin absorption, while focusing more on stabilizing the conditions of light absorption by holding the hair surrounding the optode in place using rubber teeth. It is hard to imagine that this solution may be efficient with freely moving patients, particularly since it was tested for finger tapping. A closer look is definitely warranted in order to be able to properly evaluate this design.

In general, the concept of long-term monitoring using NIRS is only being introduced recently (Yücel et al., 2014; Yücel et al., 2013), with an increasing number of publications focusing on the portability of the NIRS system. To date, there is only one published study demonstrating the use of a NIRS device in natural open air setting during a bicycle ride. This study provides a comparative look at a wearable NIRS device in three conditions: indoor sitting on a stationary bike, indoor pedaling on a stationary bike and outdoor bicycle riding (Piper et al., 2014).

The cap used in this study is shown in Figure 2-4 together with the optode design used. It is worth noting that the optode size is significantly reduced to a degree comparable with EEG electrodes. On the other hand, light is guided through a very narrow glass rod that is 3 mm in diameter in order to help penetrate the hair and maintain contact with the scalp. This is a very important improvement that has undoubtedly played an important role in reducing the motion artifact of the optodes, particularly since they are connected to a backpack portable device. However, the adoption of flexible cap design from EEG systems may still be regarded as a drawback, since as mentioned earlier in section 1.1, NIRS coupling is more susceptible to motion artifacts than EEG.

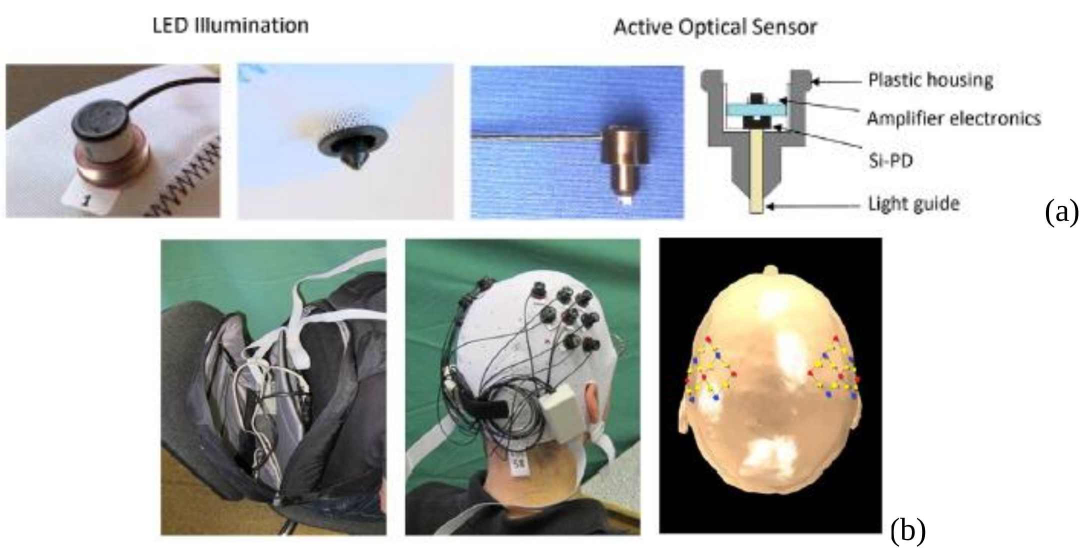


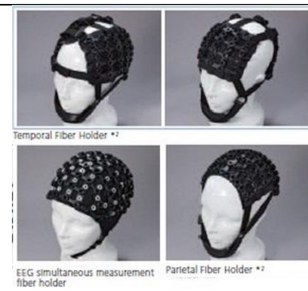
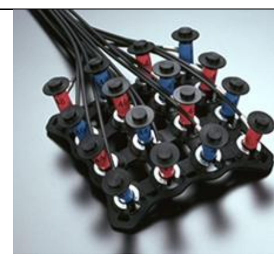

Figure 2-4: Example of a Portable NIRS device (Piper et al., 2014).: (a) miniaturized optode design showing the 3mm light guide to penetrate the hair , (b) The cap and thin wires

This assumption is further confirmed by observing the comparative results obtained in the study between the three positions. The rejected channels per person for someone sitting on a stationary bike was 5%, this value increases to 7.5% for indoor pedaling on a stationary bike and jumps to 35% for outdoor bicycle riding. While the maximum number of rejected trials for stationary and indoor pedaling sessions were 5% and 9%, respectively; this value becomes 17% for outdoor bicycle riding (Piper et al., 2014). The authors were careful to eliminate any sources of deviations between the three testing conditions, therefore the same volunteers were asked to participate in each testing configuration and to repeat the same task (hand gripping), therefore, variations between the results can only be attributed to the stability of the cap in each condition. Taking into consideration that the bicycle riding tests were carefully designed short-term sessions that were not performed in a bumpy outdoor settings, it is fair to assume that the cap was not subjected to sudden, repetitive motions that correspond with other outdoor tasks such as jogging. However, the results obtained are impressive and this is definitely a step in the right direction towards the design of completely mobile, wireless NIRS devices.

## 2.2 Commercial NIRS systems today

The first commercial 42 channel fNIRS instrument was released in Japan in 2001 and was used to study human gait for the first time (Miyai et al., 2001). Since then a lot of companies started working on multi-channel designs for portable and wireless systems (Atsumori et al., 2009; Iramina et al., 2010; Kim et al., 2011; Le Lan, 2013; Piper et al., 2014). However, wearable devices only started to make an appearance in the market in 2009 (Hitachi, Spectratech from Japan and fNIR Devices from the US) followed by new models in 2010 and 2011 (NIRx from the US, DynaSense from Japan and Artinis from the Netherlands). However only Hitachi and NIRx offered a number of channels that are 22 and 256, respectively. While Spectratech and fNIR devices presented a 16 channel portable system for the forehead area only (Marco Ferrari & Quaresima, 2012). Table 2-1 outlines some of the commercially available NIRS instruments for two major categories, portable and non-portable devices, and the design of the headwear used in each model when available. It is interesting to note that there are no tangible differences yet between the cap or "optode holder" design used with portable versus non-portable systems, with only some advancements made in relation to optode size and connecting wire thickness.

Table 2-1: Main commercially available systems and their caps

| | Portable Systems | | Non-Portable Systems | |
|---|---|---|---|---|
| Company |  | **MRRA Inc** |  | **Shimadzu** |
| Instrument | | Genie fNIRS | | LABNIRS |
| No. of channels | | Up to 1024 channels | | Up to 142 channels |
| No. of wavelengths | | 2 wavelengths | | 3 wavelengths |
| Sampling rate | | 5 Hz | | ~ 167 Hz |
| Website | | http://www.mrrainc.com/products.php?product=Product-3 | | http://www.shimadzu.com/an/lifescience/imaging/nirs/nirs_top.html |
| Company |  | **BIOPAC systems Inc** |  | **Hamamatsu** |
| Instrument | | fNIR100W | | NIRO-200NX C10448 |
| No. of channels | | Maximum 4 channels | | 2 channels |
| No. of wavelengths | | 2 wavelengths | | 3 wavelengths |
| Sampling rate | | Not available | | Not available |
| Website | | http://www.biopac.com/Wireless-fNIR-Optical-Brain-Imaging | | http://www.hamamatsu.com/us/en/product/category/5002/5022/C10448/index.html |
| Company |  | **Dynasense** |  | **Hitachi** |
| Instrument | | PocketNIRS Duo | | ETG 4000 |
| No. of channels | | 2 channels | | 24, 48 and 52 channels |
| No. of wavelengths | | 3 wavelengths | | 2 wavelengths |
| Sampling rate | | 60 Hz | | 10 Hz |
| Website | | http://www.dynasense.co.jp/english/index.html | | http://www.hitachi-medical-systems.eu/products-and-services/optical-topography/etg-4000.html#Specifications-2 |
| Company |  | **NIRx** |  | **Rogue Research** |
| Instrument | | NIRSport 88 | | Brainsight NIRS |
| No. of channels | | 64 (up to 128 using two devices in tandem mode) | | 72 |
| No. of wavelengths | | 2 wavelengths | | 2-3 wavelengths |
| Sampling rate | | 2.5 to 62.5 Hz | | 1-100Hz |
| Website | | http://www.nirx.net/imagers/nirsport | | https://www.rogue-research.com/ |

Most commercial NIRS caps for wireless and portable systems try to mimic the stretchable EEG cap concept, such as the cap shown from NIRx for their portable system in Table 2-1. However, this transfer is not successful as there are inherent differences between the two imaging systems. Primarily, EEG is not as sensitive to movement artifacts as NIRS, in addition EEG sensors are very small compared to NIRS optodes which add weight and bulkiness that tend to destabilize the stretchable material and amplify movement artifacts due to their own weight. Therefore it is not unexpected that these designs are not very successful in maintaining stability with freely moving patients, which makes them limited to short and controlled monitoring sessions.

Usually more success with regards to motion artifacts is achieved using non stretchable materials that are commonly used as patches covering a certain imaging zone, such as Velcro or polymer bands. The standard holders from Hitachi and the variety of patches from Shimadzu shown in Table 2-1 are an example of such designs. These patches are easier to install, and offer more stability for the optodes however, they are not comfortable for monitoring sessions that exceed 2-3 hours and they cannot be made to cover the entire head due to their rigidity and inability to accommodate head shape variations between different participants.

Several commercial NIRS models have limited number of channels, primarily for ambulatory purposes, such as the systems illustrated from Dynasense, Biopac and Hamamatsu, shown in Table 2-1. Such designs may be developed to combine EEG with NIRS optodes over a specific zone, and are not commonly meant for scientific research nor for extended periods of time, but focus more on easy installation and aesthetic design. An example of such a system is shown in Figure 2-5 which presents an existing EEG/NIRS strap combination in laboratory settings, versus a future model for ambulatory use from the IMEC University, Belgium. However it is worth mentioning that this design remains experimental where only the EEG system was put forth for use in the projected illustrated holder (Moore, 8 February 2011).


(a)

(b)

Figure 2-5: Future ambulatory EEG/NIRS band design from IMEC (a) lab setting of EEG/NIRS combined system (b) Portable EEG ambulatory electrode holder (Moore, 8 February 2011)

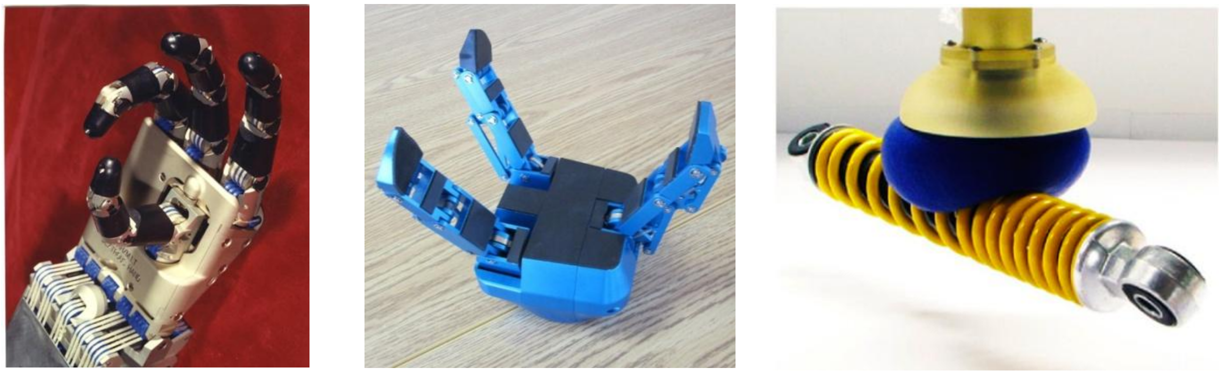
The importance of scalp contact in NIRS imaging was challenged in one recent study (Funane et al., 2013). The introduction of a non-contact NIRS scanning system is based on changing the properties of light by phosphor cells placed on the skin. Thus the optical scanning system is able to differentiate between ambient light and the light that propagates from the tissue. Then, data are collected using a "scanning" system that can flexibly change source positions (Funane et al., 2013). So far this design was tested on the human forearm and forehead, and proposes the concept of NIRS scanning instead of NIRS imaging. However, the device in its present form is too bulky for wireless use and its portability is further challenged as it has no clear method to address movement artifacts or hair penetration. Nevertheless, if optical imaging technology succeeds one day in achieving a portable NIRS scanning system, then the conditions required from a NIRS cap may change drastically.

## 2.3 Gripping the head

The need to achieve a perfect "grip" on the head in order to create a stable optode can lead us to draw a parallel between this research area and that of robotic grippers. The concept of "grasping" is a very well known definition in robotics, as it is behind the design and development of robotic arms, grippers and industrial robotic product manipulators in general. Secure gripping involves not only contacting the object, but also preventing slippage under various conditions (while the object is being moved, or under unknown disturbing forces and moments). In the attempt to mimic human hand functionality numerous research have been dedicated to analyze and recreate regular hand manoeuvres such as: reaching, restraining an object and manipulating it. But for the NIRS study requirements only the function of grasping or gripping is relevant.

Although wrenches and fixtures have been used for decades in the industry, the definition of grasping as it is used in robotics today arguably relies on work presented in the late seventies and early eighties (Asada & Hanafusa, 1979; Mason & Salisbury Jr, 1985; Salisbury & Roth, 1983). The design of grippers varies in complexity and dexterity based on the particular application required. Today, variations in robotic gripping mechanisms reflect the difference in applications they are used in, whether it is for industrial sorting purposes, where speed may be of concern, or in surgical robotic devices where accuracy and precision are paramount. Some of these designs are shown in Figure 2-6 and they reflect the wide range complexity involved in achieving this task, as designs vary from a multifingered hand design, such as the one built in Utah-MIT

(Jacobsen et al., 1986) which was powered by 32 actuators; to simpler models such as the three fingered hand powered by only four actuators (Ulrich, 1989) which introduced the concept of grasping by enveloping, in addition to the universal grippers that represent passive gripping mechanisms and are the simplest form of grippers (Amend et al., 2012; Brown et al., 2010).



(a) (b) (c)

Figure 2-6: Various types of robotic grippers: (a) Utah/MIT dexterous hand (Jacobsen et al., 1986), (b) The three fingered gripper (Ulrich, 1989), (c) Universal gripper (Brown et al., 2010)

The most important concept in robotic grippers is grasp maintenance, this is achieved by two conditions; the prevention of contact separation and sliding. In general, enveloping grasps are superior in restraining an object than fingertip grasps. If a gripper achieves form-closure it can completely resist any external disturbance irrespective of the magnitude of force. In 1875 Reuleaux proved that planar bodies require at least four frictionless contacts to achieve form closure (Reuleaux, 1875), while at least seven contacts are required for spatial cases (Lakshminarayana, 1978). Various methods to achieve form-closure on various objects have been extensively studied (Markcnscoff & Yapadimitriou, 1987; Nguyen, 1988; Ponce & Faverjon, 1995; Ponce et al., 1997).

Therefore, fingertip grasping with less than seven fingers requires frictional forces to achieve secure grasping. This introduces an additional contact condition that can affect efficient grasping which is friction. Increasing the weight of the grasped object or additional external forces such as acceleration or deceleration increases the forces necessary to maintain the grasp, which may be damaging to the grasped object or too demanding to achieve using the grasping mechanism used. On the other hand, enveloping grasps use the entire surface of the gripper (fingers and palm) to form multi point contact system and fulfill the spatial grasping requirement with less than 7 finger design and thus requiring no additional friction to maintain the grip. However friction forces are necessary in order to provide a softer hold over an object and to reduce the amount of directional force needed in maintaining a perfect grip (Ulrich, 1989).

In general, robotic grasping today mostly relies on a hand with two or more fingers and a combination of visual feedback and force sensing at the fingertips. This requires several optimization plans for finger placement and material adaptation (in order to provide friction and avoid slippage). Such a system also requires a central processor to analyze incoming data (from sensors or visual feedback) and to respond accordingly. On the other hand, passive gripping systems, where shape adaptation is performed autonomously without a sensory feedback, replace the several electronic controllers by a soft interface that molds itself around the object upon contact. Such passive securing techniques vary from a snake like gripper composed of a series of joints and pulleys with a single actuator (Hirose & Mori, 2004) to movable jaws fitted with inflatable rubber pockets (H. Choi & Koc, 2006) and elastic bags loosely filled with granular material that act as grippers when pressed against an object and the gas inside the bag is evacuated (Amend et al., 2012; Brown et al., 2010; Perovskii, 1980; Schmidt, 1978).

Gripper mechanisms can also be defined by their driving forces, these are usually electric, pneumatic, hydraulic, vacuum, magneto-rheological fluid and shape memory (H. Choi & Koc, 2006). Although electric motor grippers have been used since 1960, and still remain one of the most commonly used robotic end effectors in spite of their relative complexity, pneumatic (or hydraulic) systems have found a special use in the industry due to their simplicity and cost effectiveness. The soft pneumatic gripper developed by Warnecke et al. (Warnecke et al., 1979) was capable of handling very fragile components such as eggs. Pneumatic systems can also be used as actuators in finger type grippers in order to control the grasp force. While hydraulic force actuated sub-sea robot grippers offer a natural passive compliance to correct positioning accuracy with minimum moving parts (Lane et al., 1999).

The most important distinction between robotic gripping concepts and that of a NIRS cap, is that robotic grippers are defined as end-effectors, in that they represent only the interactive part of a larger device that is capable of applying the necessary force or mechanical manipulation for the action to take place, while a NIRS cap has to achieve complete form closure as an independent gripping unit. On the other hand, while grippers in general strive to achieve a perfect grip against slippage and in order to resist various internal or external forces, NIRS caps are required to achieve stability on every single point on the cap in order to provide optode stability and not simply maintain a general grasp on the head. Therefore, in addition to the global grasping requirements, localized gripping conditions are also paramount.

Based on this very compact account on robotic grippers, and taking into consideration the requirements of the NIRS cap design, namely: achieving contact on the whole surface of the head, applying uniform pressure throughout, light weight design and reliance on friction as a means of stabilization rather than normal force in order to maintain user comfort. The type of grippers suitable for this application narrow down to pneumatic grippers, due to their simple design, light weight and ability to conform with various head shapes. There are two types of pneumatic grippers, inflatable and vacuum grippers.

The idea of using inflatable air pockets in robotic grippers is meant to stabilize the object by adding a frictional force and increasing the surface area in contact with the object. the soft rubber material is only lightly inflated in order to provide a cushioning and engulfing affect while the grasping force itself is induced by the robotic claws or fingers of the gripper. Such a design was proposed by Choi and Koc where the role of the pockets is considered complimentary to the main gripping action, and is restricted to slippage prevention (H. Choi & Koc, 2006).

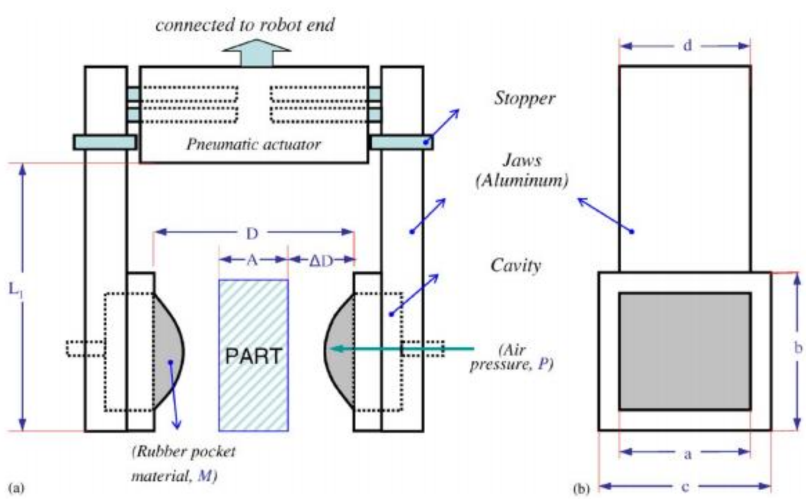
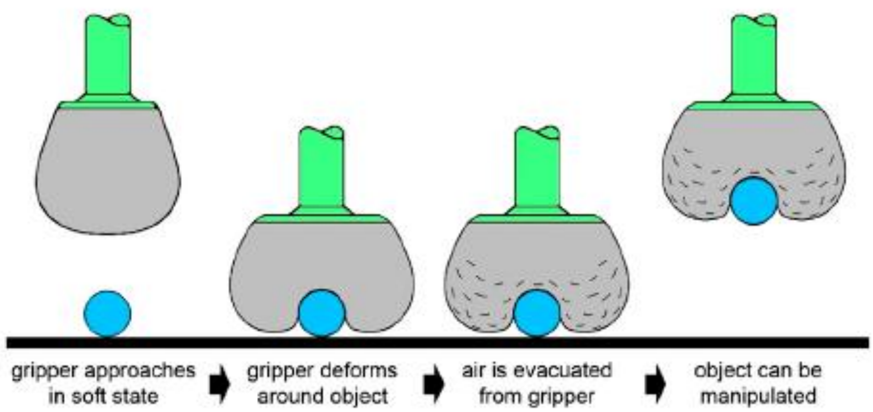


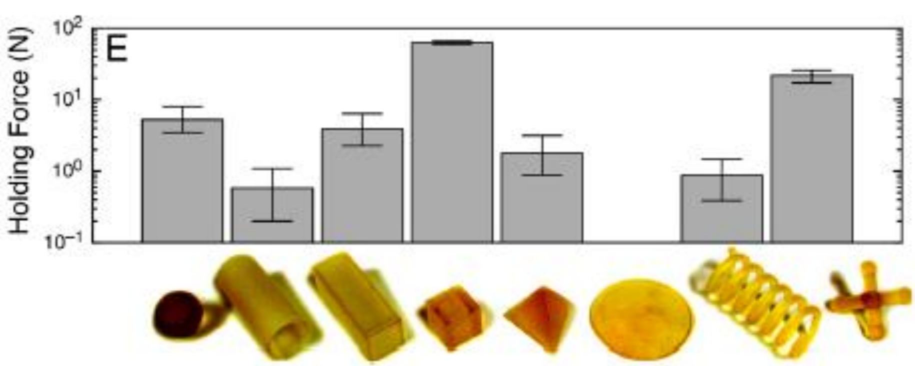

Figure 2-7: Flexible gripper with two claws equipped with inflatable pockets (H. Choi & Koc, 2006).

On the other hand, the vacuum pneumatic gripper design relies on reversible jamming transition of granular material inside an air tight flexible housing. The jamming operation is done pneumatically by creating a vacuum inside an airtight bag, forcing the granular material into a rigid tight fit formation as opposed to a free-flowing mouldable state when the vacuum condition is lifted. The formability of the bag containing the granular material is essential in creating a tight grip, as this concept relies heavily on how perfectly the bag can mold itself, whilst in a free-flow condition, to a particular shape.

This type of passive gripping systems offer a surprisingly simple solution to most gripping requirements as they do not need any feedback control systems and they are sensitive enough to handle raw eggs, in addition to their ability to handle a variation of shapes and material with a certain disparity in holding force, as shown in Figure 2-8.



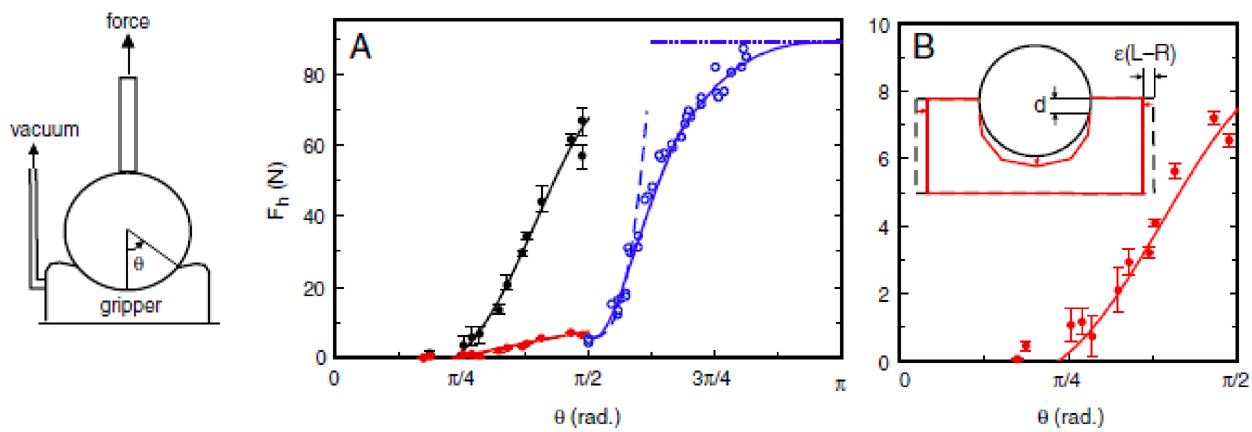

(a)




(b)

Figure 2-8: The universal gripper: (a) The working mechanism of the universal gripper that is based on engulfing the object and once contact is establish air is evacuated and a rigid grip locks the object in place (b)Variation of gripper holding force corresponding to the shape shown underneath (Brown et al., 2010)

Brown et al. presented a thorough study of the mechanisms and forces involved in this type of grippers with an in depth analysis of gripping a sphere, and identified the types of forces involved in this action. They concluded that the factors affecting the jamming function comprise the type of the contact surface and that the grasping force is enhanced by smooth surfaces. This is primarily due to the suction force created by taking the shape of the gripped object which drops significantly for porous or rough surfaces. Another important factor is the enveloping degree of the shape that is being gripped, this can be identified by a contact angle θ shown in Figure 2-9a. Based on experimental results, for contact angles below π/4 the gripping strength vanishes except for a small contribution due to residual membrane stickiness, however for higher contact angles even a porous or rough surface can be gripped with a high holding force Figure 2-9b.




(a) (b) (c)

Figure 2-9: Experimental setup to measure the effect of contact angle on holding force: (a) System overview, (b) The black line shows the variation of the holding force versus contact angle for a solid sphere, the red line represents a porous sphere, while the blue shows the results of geometrical interlocking for contact angles above π/2 for a porous sphere, (c) Sketch of the contraction that occurs when a gripper of diameter L jams around a sphere of diameter R producing an O-ring like pinching region of width d (Brown et al., 2010)

The evacuation of the air inside the gripper causes a differential pressure ($P_{jam}$) across the membrane which results in a volume contraction that jams the granular material inside the bag and tightens the contact between the bag and the object. The contraction of the elastic bag forms a contour that resembles an O-ring around the periphery of the object that holds it with an applied stress of magnitude σ centered at θ. This results in a normal force on the sphere that can be found to be:

$$F_N = \sigma A \sin\theta \tag{2.1}$$

where A is the area under the pressing normal force. This gives rise to a tangential friction force of magnitude $\mu F_N$ where $\mu$ is the static coefficient of friction at the membrane/object interface. The force necessary to induce slippage is:

$$F_f = F_N(\mu \sin\theta - \cos\theta). \tag{2.2}$$

Moreover, the holding forces are proportion to the confining pressures Pjam with a maximum holding force equal to:

$$F_h \sim P_{jam}R^2 \tag{2.3}$$

This can be used to estimate the gripping forces per object, as the holding forces scale with the area gripped. Finally Brown et al. concluded that neither the bag geometry nor details of the granular material inside the bag seem to have a high effect on $F_h$, as the most important factor seem to be the conformability of the bag itself to the shape of the grasped object (Brown et al., 2010).

## 2.4 Summary

This chapter reviewed previous efforts dedicated to creating a stable brain-device interface for NIRS imaging. It is obvious that a significant part in achieving a truly portable NIRS imaging system relies on the design of a successful interface, which represents the single obstacle today against a fully portable imaging device with freely moving subjects. The importance of NIRS caps can be summarized with a statement from one of the most prominent companies in NIRS imaging, Rogue Research:

> "You can have the most sensitive detectors in the world connected to the best amplifiers, but if the optode is not in good contact with the scalp, all of this is wasted. One of lessons learned over the years is that there is no one solution that suits all needs" (Rogue-Research, 2014).

There are however major gaps in the identification of some engineering parameters that can be associated with portable NIRS caps, such as the pressure value necessary to create a stable optode, versus the pressure range associated with comfort on the head. Moreover, considering the limited success of traditional NIRS imaging caps the possibility of adaptation of new mechanical concepts in order to achieve a successful design opens the door towards other areas of research, such as robotic grippers. In general, an ideal case for a NIRS cap would be equivalent to a glued on layer of NIRS optodes, where every single location of the cap perfectly resists slippage as well as localized detachment. However, in the absence of such a solution, the creation of a system that can closely approximate these conditions while maintaining ease of installation and flexibility can be regarded as an important improvement over present solutions.

The following chapter presents several NIRS cap adaptations of commercially available solutions and how they were modified to fit the Imaginc group NIRS system. Which presents an important step in identifying the advantages and disadvantages of each solution.

# CHAPTER 3

# DIFFERENT NIRS CAP DESIGNS

The NIRS cap, as a non electronic part of this imaging system, has been largely left out of active studies, due to the fact that interest in imaging fully moving patients has only emerged recently. In order to fully investigate the efficiency of available solutions, several cap designs were manufactured during the course of the project. All commercially available NIRS caps were explored as well as possible adjustments on these designs and some adaptations of EEG caps. Other design possibilities were also investigated in order to attempt a more comfortable brain imaging headwear that can conform to head shape variations. The advantages and disadvantages of these designs were documented by employing the caps in different imaging projects conducted by several collaborators, and modifications were made based on their feedback.

Additionally, the hair removing process was addressed in order to alleviate cap installation and present possible solutions that can comply with single user applications necessary for BCI.

This chapter focuses on the different models developed throughout the project, their manufacturing process, possibility to evolve and basic shortcomings.

## 3.1 Addressing the issue of comfort

One very important aspect in realizing comfort in a tight headwear is to make sure that the cap conforms to the head shape completely, this ensures that the pressure is equally distributed throughout without any areas undergoing excessive pressure while other areas lack contact. On the other hand, stretchable material used in several commercial EEG and NIRS headwear, such as the one used by (Piper et al., 2014), that are capable of achieving a certain degree of head shape conformability tend to create more noise with moving and talking subjects due to optode displacement. Therefore, in order to address this issue two types of caps were fabricated: a tissue cap stuffed with foam sheets, and molded foam cap designs. Both were made from non-stretchable material, in order to stabilize the position of the optodes on the cap. The relative softness of the material was intended to be used as cushioning and a shape forming means.

### 3.1.1 Textile cap padded with foam.

The textile cap shown in Figure 3-1 was a first attempt to create a cap that is comfortable and easy to install at the same time. The design was based on the remarks of our research collaborators at St. Justine hospital (Sawan et al., 2013), and a model they developed for NIRS imaging with infants. The cap was made of two layers of non stretchable cotton textile padded with foam. The cap was divided into a main circumference and additional strips that can be attached to the main piece with Velcro. Dividing the cap into several independent strips aims to facilitate the hair tossing procedure from the sides of each strip and provide head size adaptability by allowing additional pieces to be added as required by the imaging process. Both tissue and foam padding were punctured to allow optodes to reach the scalp. The optodes were made to fit in the holes and their movement was restricted due to the tight fit and cushioning provided by the foam.

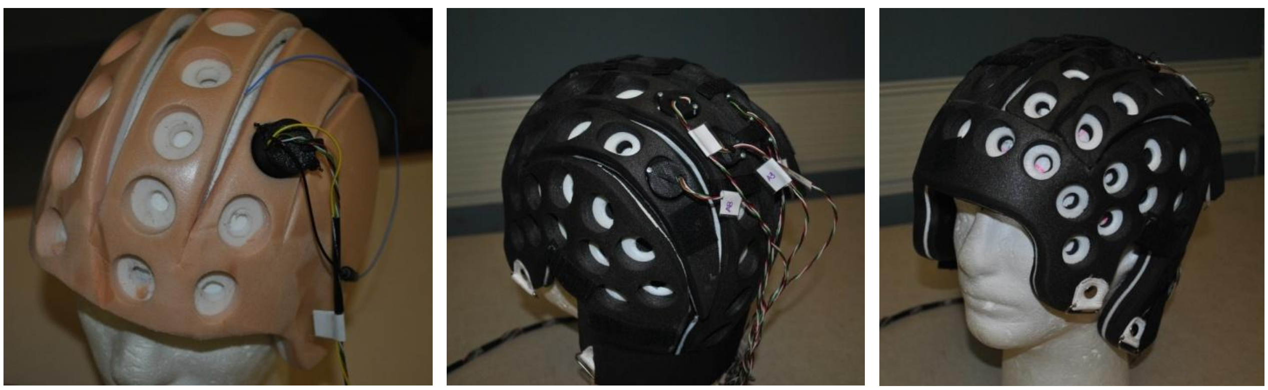
(a) (b) (c)

Figure 3-1: Textile cap padded with foam: (a) The main circumference piece, and one strip 3cm wide containing four optode locations, (b) Front view of the cap, (c) Side view of the cap in order to show that the material used does not conform fully to the head shape

The foam used in this design (2.5 cm thickness foam padding) had a high compressive rate vertically, however it was unable to conform to the roundness of the head as shown in Figure 3-1c. In addition, the use of independent strips attached by Velcro only added several unwanted degrees of freedom to each separate strip, requiring additional Velcro attachements to join them together. In retrospect, adopting the design that was used with infants to a full head NIRS cap for adults was not successful due to many issues: optodes used with infants are set in their position as they are encased in a latex strip, therefore the infant cap only confines this strip using a padded and comfortable headwear, which is not the case in adult NIRS devices. On the other hand, the longer strips that are used with the bigger head size are harder to stabilize and apply the necessary pressure to help with hair tossing. However, having fully encased optodes remains a very interesting solution for studies that require overnight monitoring of a small localized zone.

### 3.1.2 Molded Foam cap

These caps were made using a special type of foam that can be molded and shaped with heat. This foam is used as a special padding for helmets and medical braces. The fabrication of the caps was undertaken at St. Justine Hospital at the orthotic and prosthetic service center (service orthèse-prothèse de St. Justine). As shown in Figure 3-2, several caps were made using this concept in order to provide a certain flexibility to the design by making part of the cap fixed, and the rest into separated strips attached at the front. This was a development from the earlier concept that relied on completely separated strips of foam, which was not easy to stabilize. The foam strips were then joined together at the back using Velcro bands, and the optodes were secured inside the foam with a tight fit.



(a) (b) (c)

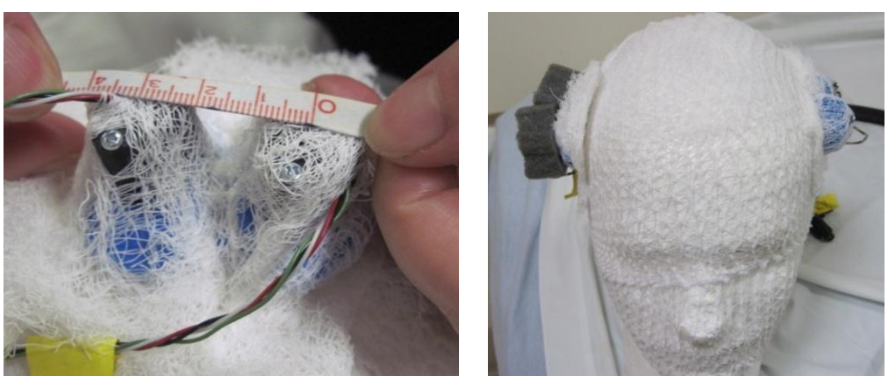
Figure 3-2: Heat molded foam cap design: (a) First attempt at creating a foam cap from a single piece of foam, (b) Later development of the concept using molded foam circumference piece glued to stripes that are attached by Velcro at the back, (c) Front view of the cap showing the glued stripes at the front

In spite of the added attachments to secure this cap, such as the Velcro bands and the side metal braces that allows to hold the cap down using a belt under the arms, this cap was also unable to conform with head shape variations or apply the necessary pressure to secure the hair and optodes in place. Its thickness, while important to engulf the optodes, was not ideal to ensure contact at all locations.

This concept may be interesting for devices that have smaller optodes with less thickness. Still, adopting this type of material would be ideal if heat remolding is made possible in order to adjust the cap into the head shape of individual participants. However, considering how laborious such a solution may be, this idea was not pursued any further and alternative solutions were attempted to achieve this aim.

## 3.2 Stable cap designs

Addressing the issue of absolute optode stability for long-term applications has to take into consideration other possible means for achieving this goal without using pressure as the main mechanism. Such a solution is possible by gluing the optodes in place, much like the work reported previously with EEG and NIRS fiber optic systems (Yücel et al., 2014; Yücel et al., 2013). The glue used to stabilize EEG electrodes and NIRS fiber optic optodes is collodion, which is a pyroxylin solution. Since this system was used with epilepsy patients to allow monitoring over days (even a week) the possibility of using this system with portable NIRS devices had to be tested. However, given the optode size disparity between fiber optics/EEG electrodes and portable LEDs, the optodes required additional support to keep them in an upright position and to avoid getting them detached due to their own weight. The results obtained are shown in Figure 3-3. Two different types of support or foam dressings were used to hold the optodes on the head, after which the traditional procedure of adhering was used by surrounding the optode and the support with gauze and gluing them in place using collodion, after which the collodion was dried using an air blower.



(a) (b)

Figure 3-3: Fixing the optodes on the head: (a) The minimum distance between optodes is approximately 4 cm due to the added foam support, (b) The shape of glued optodes on the head

Using this method, the minimum distance obtained between the two optodes was ~4 cm due to the height and size of the optodes. Such a solution can be possible only by minimizing the optode size into a "flatter" configuration that would allow it to be placed into an array and glued in place properly. On the other hand, the use of collodion may not be practical outside hospital settings for monitoring in natural conditions. While the extensive installation procedure may be justified for 24h and up to a week of monitoring; however, for shorter periods with freely moving subjects, this is considered a fairly laborious and excessive procedure.

On the other hand, in considering possible cap solutions that are based on commercial designs and with the absence of foam padding that would secure the optodes in place, other means of attaching the optodes on the cap are necessary. Therefore, a socket design and corresponding optode housing were made for this type of caps. The designs of the socket and housing were modified in later models in response to improvements on optode size and to create spring loaded optodes that ensure contact with the scalp. Figure 3-4 show design developments of both socket as well as housing for the ~2cm in diameter PCB optodes that were made initially.

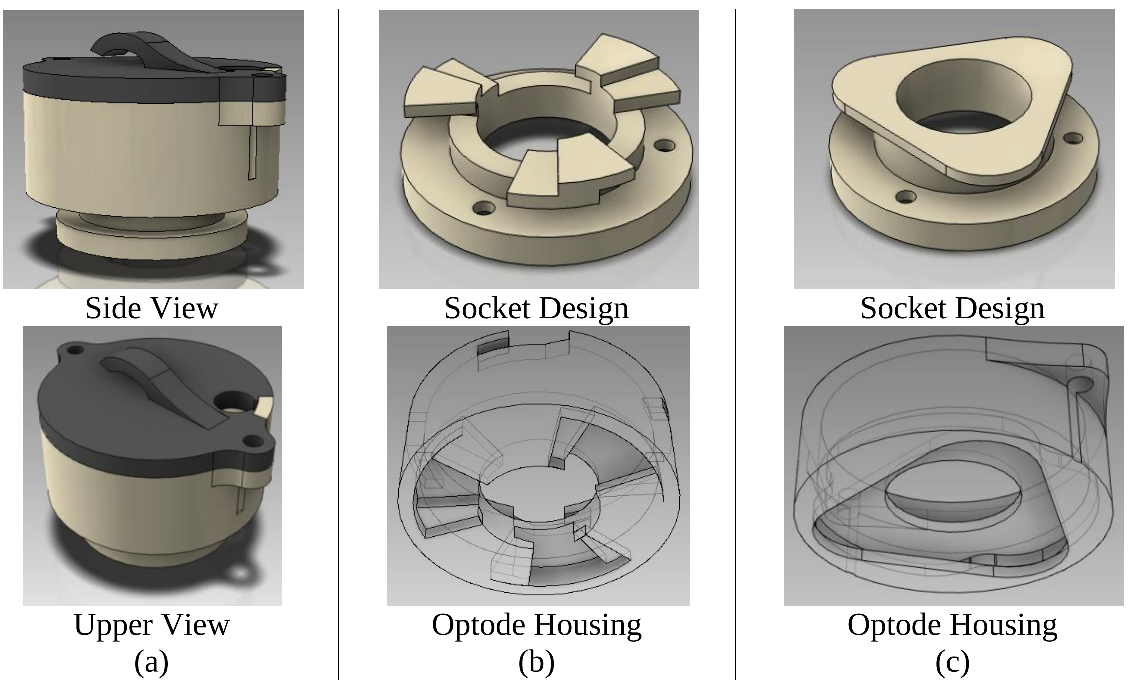



Figure 3-4: Optode housing design for a PCB of ~ 2 cm in diameter: (a) Optode stabilized on the head by a small lip that helps jam the optode due to the applied pressure of the cap without a socket, (b) First socket and corresponding optode design with angular interlocking lips, (c) Second optode and corresponding housing design for a better interlocking mechanism

The optode housing shown in Figure 3-4a is the only model that was not coupled with a corresponding socket, instead it relied on the small relief beneath the optode to cling to the cap material benefiting from the tight cap pressure in order to secure it in place. This mechanism was not sufficient though to ensure optode stability, which is why it was not pursued any further. On the other hand, the optodes and corresponding sockets of parts b and c of Figure 3-4 show developments of the attaching method, which was necessary in order to overcome the fragility of the locking mechanism in Figure 3-4b. These models were made for the early ~2 cm in diameter PCB, which was later on modified to a smaller optode design that is used presently.

The latest optode housing and sockets, used by the Imaginc team, are shown in Figure 3-5, the new PCB, ~1 cm in diameter, allowed for a better distribution of optodes on the head, in addition the design was equipped with a spring gently pushing the optodes in order to ensure efficient scalp contact.

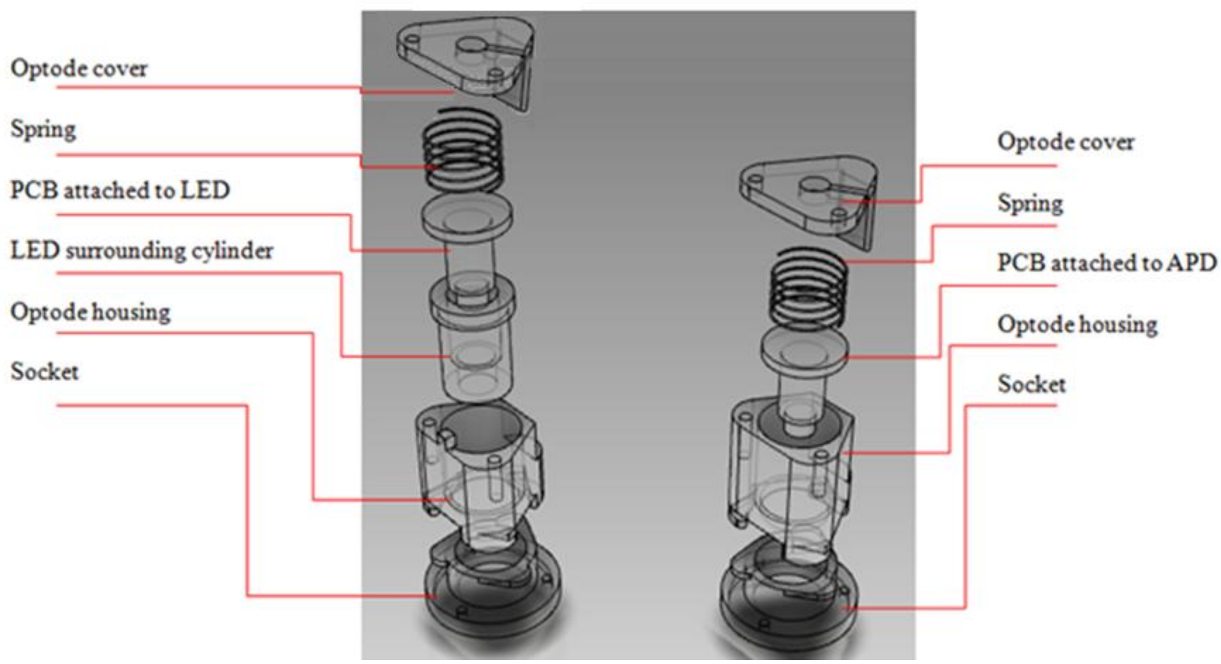
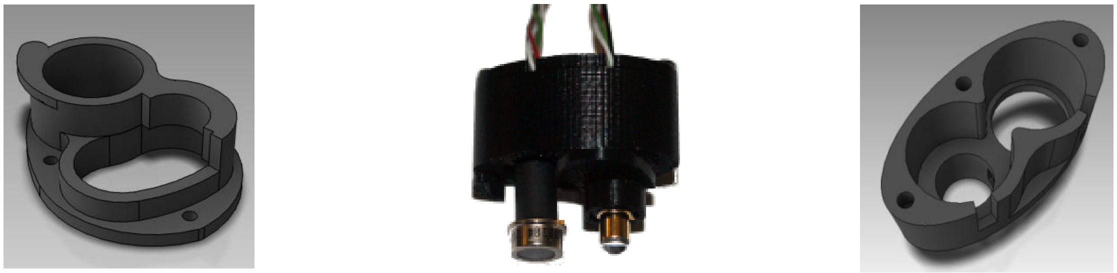



Figure 3-5: Spring loaded optode design for ~ 1cm in diameter PCB, the spring loaded system allows more normal force pushing the optode gently to stabilize it on the scalp

In addition to the single optodes, double optodes were developed where an emitter and a detector are placed 1cm apart in order to filter the registered data by measuring and extracting extracortical hemodynamic variations (Gagnon et al., 2014). The special socket and optode housing design for these short channels are shown in Figure 3-6.



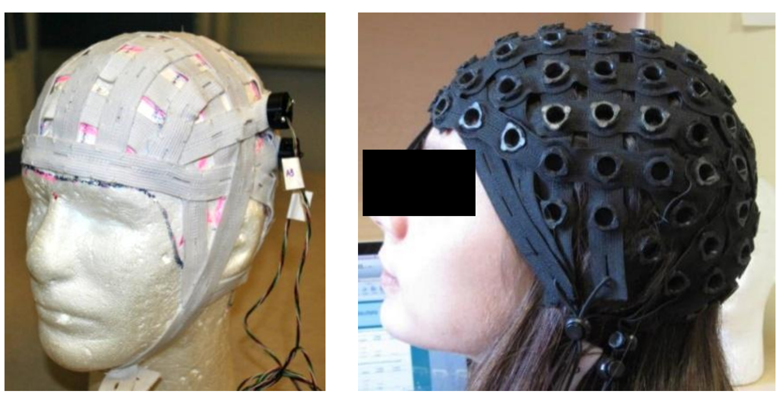
**(a)** **(b)** **(c)**

Figure 3-6: Double optode socket and housing design for small distance channels: (a) Double optode socket design, (b) A photo of the double optode socket with the two PCBs installed, (c) The double optode housing on the inside showing the location of the two PCBs

### 3.2.1 Cap design without integrated sockets

The first caps constructed in order to validate the Imaginc team NIRS device were not equipped with sewed on sockets to hold the optodes in place. Instead they provided small openings to hold the optodes due to their tight fit. The two most important models developed were the elastic band cap and neoprene elastic caps. These caps were compatible with the optode housing design in Figure 3-4a.

The elastic band cap: Derived from EEG elastic caps available commercially, such as *HydroCel GSN130 EGI*, this design aims to provide a tight fit while allowing enough openings on the head for ventilation and easy hair tossing. In the absence of sockets to hold the elastic band openings in place this design was not practical, Figure 3-7(a). However, the idea was revisited later on, and with the fitted sockets in place, it is presently being used with epilepsy studies for short term resting patients monitoring, Figure 3-7(b).



(a) (b)

Figure 3-7: Elastic band cap : (a) Elastic band cap without sockets, (b) Elastic band cap with sockets

This solution offers easy installation and a tight fit that is capable of conforming to various head shapes. However, the flexible material of the cap itself cannot offer dynamic stability with freely moving patients, as movements of the head may cause certain areas to expand affecting the distance between the optodes. On the other hand, in spite of the tight fit design of this model, it still requires additional attachments to a belt under the arms in order to avoid cap slippage (where the cap starts sliding backwards). This design can be used in short-term monitoring applications, where no head and chin movement are needed, such as gait, however it is not suitable for long term monitoring applications.

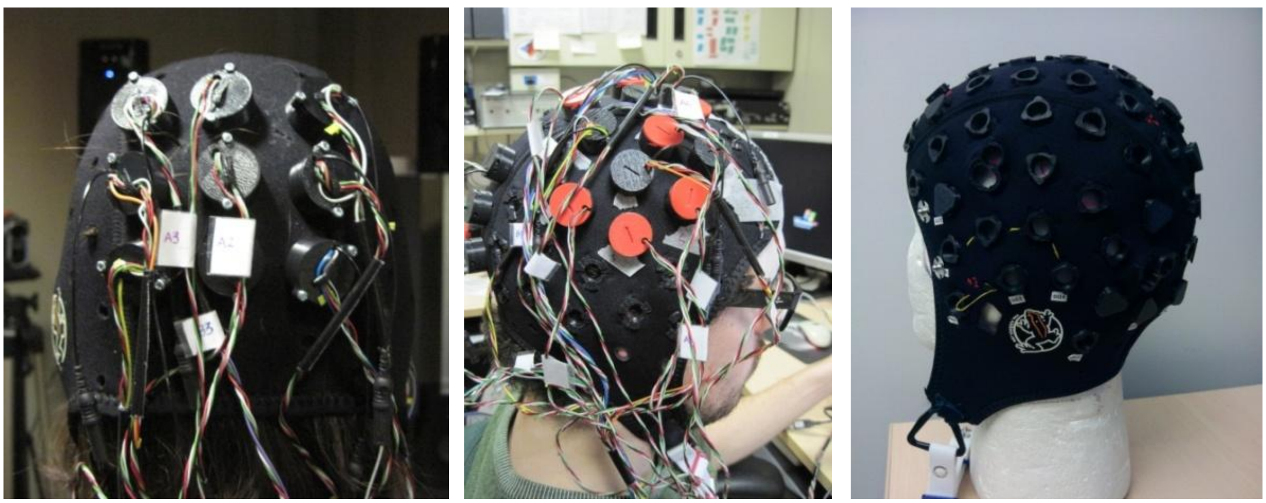
Neoprene cap without sockets : Neoprene caps are made of diving hoods that were cut in order to provide more freedom at the neck and optode openings were punched-in with small diameter steel tools at 3 cm distances. This material was successful in providing relative stability and comfort, allowing certain conformity with head shapes, although certain areas, particularly the temporal zone, were problematic as they generally lack the necessary pressure in order to ensure stability. The neoprene thickness used was ~2.5 to 3 mm which was stable enough without creating problems for the optode installation process. However, tossing the hair was not particularly easy through the small openings that did not provide any hair stabilizing mechanisms once it was tossed. In general, neoprene caps are the closest to commercially available complete head covering NIRS headwear nowadays, they offer relative stability when no head motion is required, due to the flexibility of the material. On the other hand, heat insulation properties of this material can cause discomfort over longer acquisitions and the flexibility coupled with lower pressure enforcement does not translate into total head shape conformity, making universal usage of such a cap not viable.

### 3.2.2 Caps with integrated sockets

The importance of the addition of sockets in general stems from providing a tight fit around the optode that allows for securing the hair in place. This was improved even further by the addition of an elastomer O ring (A65 Durometer, MIL-Spec Buna-N) underneath. The relative softness of the O ring provides certain cushioning to relieve the localized pressure of the cap on the head, this is shown in Figure 3-8.

Figure 3-8. Elastomer o-ring under the sockets that is glued underneath all sockets

The two main categories that were made with fitted sockets were the neoprene and Velcro caps. The neoprene cap advantages and issues were discussed earlier in section 3.2.1. Figure 3-9 shows the various models made in concordance with the different socket designs.



(a) (b) (c)

Figure 3-9: Development phases of full head covering neoprene caps: (a) Without socket design, (b) Socket with angular interlocking design, (c) Socket with a simple interlocking mechanism

Although these caps were used to validate the NIRS device of the Imaginc team group, they are no longer employed in research with various collaborators, as they lack relative stability with movement, and require long and laborious installation. As for full head covering solution the elastic band cap was superior to this design on both counts. Various testing with different design alterations using neoprene accounts for the confidence that this type of solutions cannot be used with freely moving subjects either for short or long-term applications.

<u>Velcro caps</u> : Since the major issue with neoprene caps was the elasticity that made it particularly sensitive for movement artifacts, head patches covering certain cranial zones were suggested using rigid material such as Velcro patches that were made compatible with our system.

The first model was an adaptation of the systems used in the Geriatric Center of Montreal, in order to validate the Imaginc device using a comparative study at the exact imaging positions. This Velcro patch is shown in Figure 3-10a. The Velcro patch has a higher spatial resolution compared to the neoprene caps, as the optodes are divided into 3 cm apart rows, while the distance between the optodes on the same row was ~2.5 cm. It also provides easier installation due to the fact that it was not made into a full head covering band. Therefore, this solution was popular and it was behind several various models that were made to accommodate the needs of other collaborators.

(a) (b) (c)

Figure 3-10: Velcro cap designs: (a) Velcro patches, (b) Frontal area covering Velcro patch, (c) Adjustable Velcro patch with the possibility to add extra bands as needed

The design shown in Figure 3-10b is currently being used for a 1 year study at the EPIC Center of Montreal for gait and has shown very promising stability albeit for short-term duration based on the accompanying survey (study in progress). Participants in this study were asked several questions regarding cap comfort and portability. Data collected include participant's head circumference, type of hair and any additional remarks they might have regarding the installation process or the cap comfort. An example of this questionnaire in shown in Appendix 1. Over 95% of the participants showed willingness to wear the cap for up to two hours, although they all agree that the cap is comfortable, with a single participant out of the 25 participant to date expressing discomfort during the installation process (study in progress).

Other regional caps were also made, as shown in Figure 3-10c, in order to demonstrate an adjustable Velcro patch system that can allow for additional pieces to be added in order to fit various head sizes and shapes. This idea was not particularly successful, as it is very hard to stabilize additional patches which adds to system installation complexity.

Other combination models using neoprene patches together with Velcro attachments have also proved to be very useful and more conforming with the shape of the head. The cap shown in Figure 3-11 was used in short-term applications at St. Justine Hospital's neurological center.

(a) (b) (c)

Figure 3-11: Neoprene-Velcro cap: (a) A view of the cap in an open position where all the Velcro adjustable attachments at the middle are undone, (b) A front view of the cap showing the adjustable elastic band on the prefrontal area, (c) A back view of the cap showing the adjustable connections on the top and the fixed elastic bands at the bottom for easy installation.

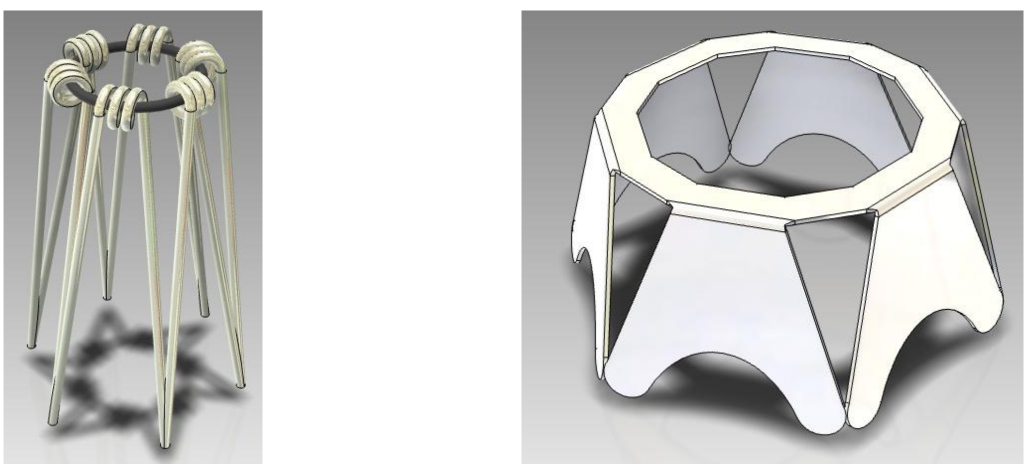
## 3.3 Addressing NIRS cap installation

Presently, NIRS cap installation requires the assistance of an expert technician and may take up to one hour for a full head covering study, such as in epilepsy monitoring. Amongst the various installation procedures that were detailed in Section 1-3, the singly most time consuming one is hair tossing, which has to be done very efficiently in order to secure the hair surrounding the optode and ensure that it will not be displaced during the monitoring process. This is important, since loose hair can either move in front of the optode causing fluctuations in light absorption, or act as a spring pushing the optode outwards and destabilizing it. The best commercial solutions offer easier access to toss the hair via larger openings around the optode location, such as in patches or with the elastic band cap designed by our group discussed herein. However, these solutions still require the aid of a technician and cannot be used with single user applications, which will be essential for future BCI devices.

In general, hair cannot be tossed if the cap does not induce sufficient pressure on the head, since the tossed hair needs to be secured in the area surrounding the optode location. Also, given the small size of the optode, which is approximately 1 cm in diameter, the hair tossing mechanism has to be simple enough in order to fit in such a tight space. In addition, hair directionality plays an important role in determining the tossing direction, specially with long hair. Therefore the design has to be flexible to fit sockets located on different parts of the cap and facing various hair directions. Several hair tossing mechanisms were studied over the duration of the project, but mostly they can be grouped into two major concepts and are the subject of the next sections.

### 3.3.1 Hair Removing Springs

This proposal was intended as an independent hair removing apparatus that is easy to use with any NIRS device. Inspired by hair styling accessories, this spring system can disperse hair in all directions in a circular fashion once it is placed and pushed downward at any optode location. The pin is then secured by the cap and socket itself and stabilized permanently by the optode to be released once the cap is removed. The wiry design of this spring is shown in Figure 3-12a. However, the design was hindered with several manufacturing challenges due to the small dimensions of the spring and the sharp angles that the spring material could not provide.



(a) (b)

Figure 3-12: Hair removing tools: (a) Spring wire, (b) Spring plate, these designs were not manufactured due to the high level of detailing that was not possible to produce with spring metal

The design was modified into a spring plate, shown in Figure 3-12b, following the same principle of the spring wire. This was also not pursued further since the design has to be able to push the hair from the middle of the socket outwards while providing a space for the optode to be in contact with the scalp.

The idea of designing independent hair removing mechanism is very interesting as it can be used with any NIRS system, however the level of detailing and the complexity of the function itself was too overwhelming for an independent unit.

On the other hand, incorporating similar designs to the optode itself is not practical since it will be far more difficult to check the hair clearance at an optode location if the tossing mechanism itself was attached to the optode, and can be undone by displacing the optode, which makes visual inspection of these locations unattainable. Therefore the design concept shifted to the socket itself as a hair clearing mechanism.

### 3.3.2 Hair Removing Sockets

The principle of a hair removing socket is easier to manufacture given that various restrictions on spring manufacturing do not apply in this case. Moreover, sockets manufacturing is possible in-house at Polytechnique Montreal using the 3D printing machine at the mechanical engineering department. The design, on the other hand, has to account for two key mechanisms: a moving part in order to toss the hair, and another stationary one in order to ensure optode stability and provide the locking mechanism needed for the moving part and the optode.

Several hair parting mechanisms were studied, they reflect how versatile the hair tossing concept is and are shown in Figure 3-13. The design concept in part (a) of this figure relies on two pins that part the hair from the middle sideways, this is advantageous as the amount of hair is divided into two parts insuring hair clearance in the middle which is the most significant area for the imaging task. However, this design cannot accommodate other hair parting directions that may be necessary based on the socket location, which may require additional moving mechanism to turn the socket around. The hair clearing concept in Figure 3-13b on the other hand, relies on a single pin that can be placed in any of the three holes provided on the stationary socket. This solution offers three different parting directions with a single pin, the simpler concept can facilitate manufacturability, however, the design needs to be tested in order to determine how successfully a single pin can provide hair clearance. The concept shown in Figure 3-13c presents the most convenient hair parting mechanism, as it is not bound with hair directionality. It relies on several pins that separate the hair from the middle outwards. Although this concept rehashes the spring clearing pin concept and was deemed too difficult to manufacture, a modified version of this design that relies on collets can be made into workable prototype for a hair clearing socket.

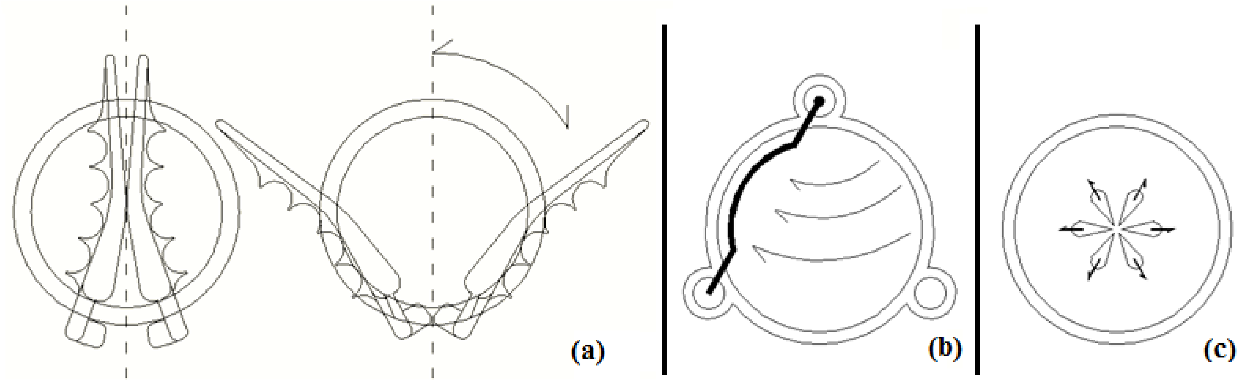
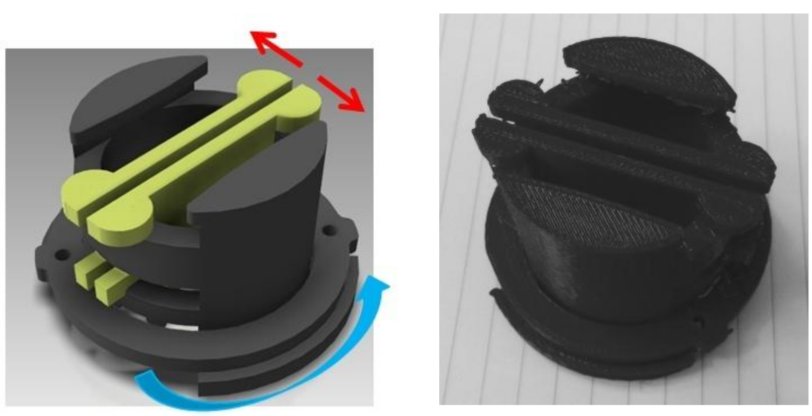



Figure 3-13: Hair parting methods: (a) dual parting, (b) single parting (c) multiple parting

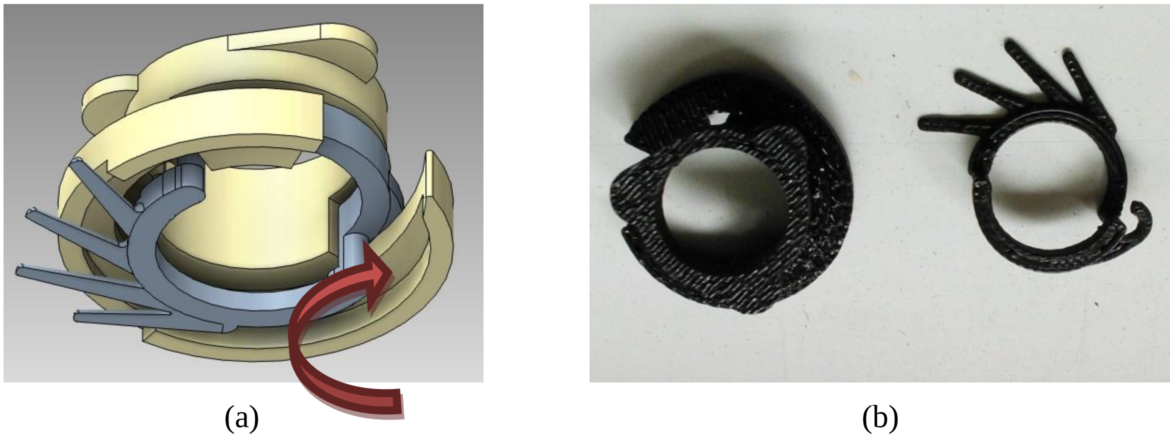
Dual parting mechanism: In order to compensate for the single directionality of the hair parting mechanism, the moving parts were increased to include a rotating mechanism as shown in Figure 3-14. However, this design was not successfully manufactured due to numerous details that the 3D printing machine was unable to provide. As expected the two pins concept was too crowded for the small clearing space available.



(a) (b)

Figure 3-14: Dual pin hair removing socket with rotating base: (a) The designed model, (b) The printed model

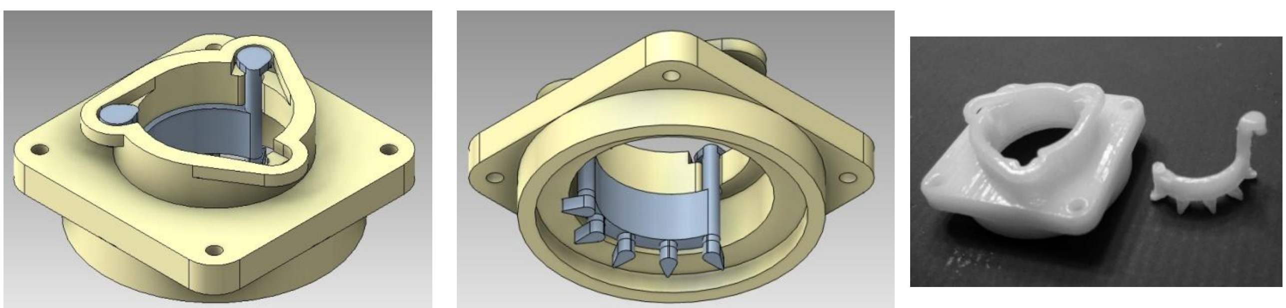
Single hair parting pin mechanism: This concept was developed into two solutions, the first one is shown in Figure 3-15 and presents a parting pin that is fixed on one end, and can toss the hair by sweeping and engaging with the stationary part, this solution however does not provide several parting directions.



(a) (b)

Figure 3-15: One pin hair removing socket with a single parting direction: (a) The designed model, (b) The printed model

On the other hand, the design presented in Figure 3-16 shows one pin with three parting directions.

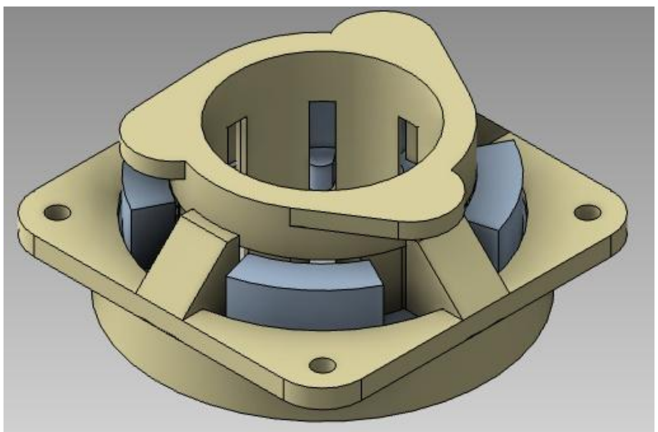


(a) (b) (c)

Figure 3-16: One pin hair removing socket with a single parting direction: (a)Designed model a top view, (b) Designed model a bottom view showing the pin, (c) Printed model

Both of these solutions were tested with advanced 3D printing technology (Stratasys, 2014), for several alterations. While the single parting direction is sturdy enough to be used with actual models, however it is not easy to manipulate and handle. On the other hand, the three parting directions presented in the second model was too fragile for use even with the better quality models.

Multiple parting directions using a special collets design: This design is shown in Figure 3-17, it relies on a stationary ring that is divided into 8 parts with pointed ends at the bottom and a rotating part that can turn to either push these “pins” to the middle of the socket (closed position) or allow them to return to their natural position (open position). Thus, the sockets are usually kept in a closed position, and once the cap is installed and fixed on the head, the rotating ring will be turned in order to bring the socket into an open position that tosses the hair from the middle and allows optode placement.



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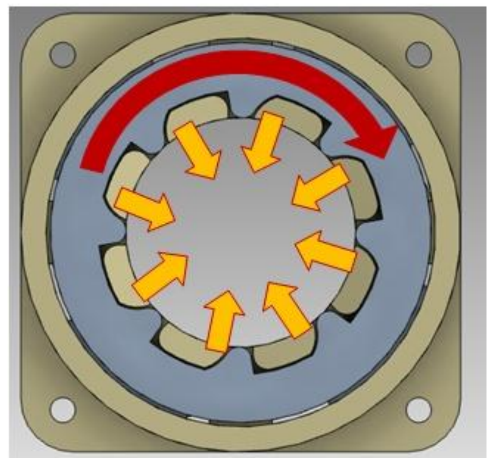

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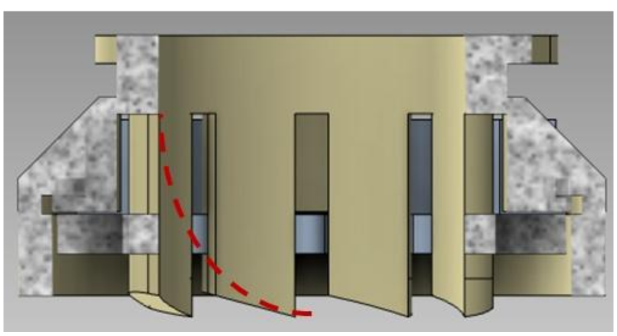
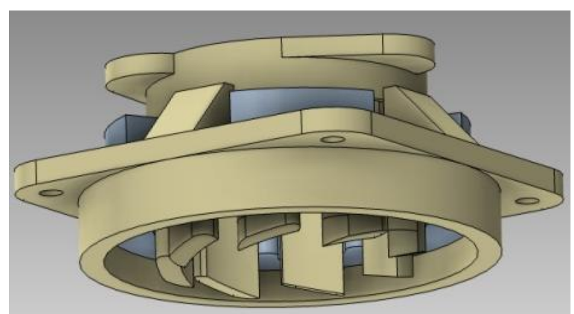


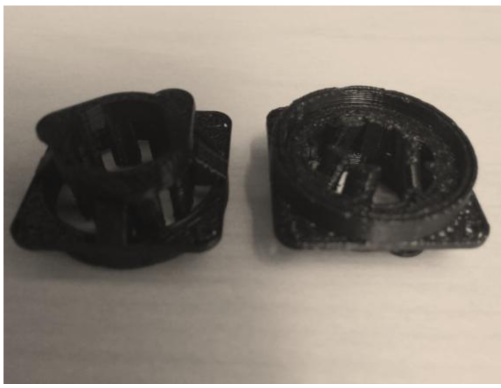
(c)



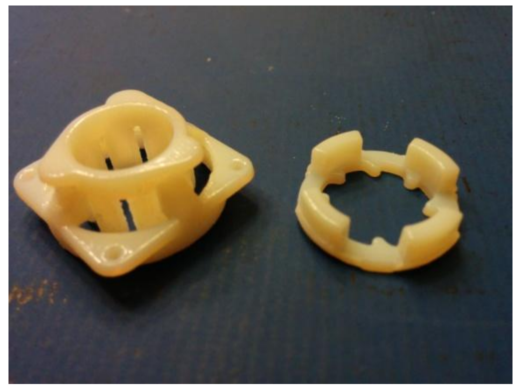
(d)

Figure 3-17: Multiple parting direction hair clearing socket design: (a) Top view, where the blue part presents the rotating ring that can either close the pins into the middle or allow them to return to their naturally open position, (b)Bottom view showing the ring rotating movement and the pins closing movement., (c) Sectional view showing the shape of the pins once the ring is "closed", (d) A side view showing the elongated profile of the pins that allows to part the hair

This design is by far the most promising. Although several alterations are still required in order to fine-tune the working mechanism of the socket, however, with the advanced printing capabilities the possibility of obtaining an elastic pin structure versus a rigid socket allows for an easy manipulation of the system. The simplicity in handling the hair clearing motion is also essential as it allows for a single user to perform the hair clearing operation without assistance. This model will be used in future NIRS caps designed for the Imaginc group, and will be put to test with our collaborators for further improvements. Figure 3-18 shows the printed preliminary model and the pins in a semi closed position.



(a)



(b)

Figure 3-18: The printed models of the collets based hair clearing socket, (a) model printed at Polytechnique Montreal (b) Model printed with the Objet printer

Chapter 4 presents experimental results obtained in comparing the different cap designs for short term freely moving subject applications. It also identifies the essential parameters that are associated with a successful NIRS cap design: the pressure values associated with optode stability and the comfort pressure threshold.

# CHAPTER 4

# EXPERIMENTAL RESULTS

As was introduced earlier, identification of basic parameters in relation to pressure associated with the cap to ensure optode stability as well as patient comfort were not accomplished so far. Recognition of such parameters provides the possibility of evaluating future NIRS caps for their suitability to various imaging tasks, ranging from a static, to freely moving subjects based on the pressure value they induce on the head. On the other hand, normalized pressure values can be used as tangible engineering indicators in order to create a suitable NIRS signal filtration system based on optode/scalp contact information. This can be possible using active feedback from dynamic pressure sensors connected to the optodes. Moreover, by recognizing the comfort pressure threshold, which can vary slightly from one patient to another, the pressure induced on the head can be optimized to ensure a positive experience for the person using this imaging system, based on the type of acquisition needed (either short or long term) or the person being monitored (based on age, health... etc.).

On the other hand, in order to clearly determine the limitations of existing NIRS caps, the three most common imaging cap models were tested for stability under three distinct conditions: rest, head movement and walking.

This type of validation and system parameter identification was never conducted before, and it presents a first step towards advancing the development of future NIRS cap designs.

## 4.1 Quantification of Stability and Comfort

### 4.1.1 Contact pressure and comfort

It is a common agreement between neurologists and researchers that the greatest advantage of NIRS is that it allows imaging of freely moving people as long as the optodes position on the head are stable. In addition, movement artifacts caused solely by movement of the person wearing the device can be filtered out using an accelerometer or various other signal processing algorithms (Iramina et al., 2010; Kim et al., 2011). However, achieving NIRS optode stability has been challenging, even during immobile testing. This is largely affected by the tightness of the cap that can be translated to as a localized pressure value at various areas on the head. In most caps, and due to variations of head shapes, some areas of the cap would lack sufficient amount of pressure to ensure contact, while other areas will cause increased pressured values that lead to discomfort.

The concept of head wear comfort was also not studied or defined previously in spite of numerous research identifying comfort in relation to hospital garments (Barker, 2002) or dynamic comfort pressure for tight clothes such as sportswear (Ge et al., 2011; Seo et al., 2007) and girdles (J. Li et al., 2012; Makabe et al., 1991).

The concept of comfort in general has a much broader definition than merely the pressure value induced, as the assessment of fabric comfort using mechanical properties cannot account for all the major factors and variations in human perception. In 1991, Raheel and Liu defined "fabric hand" as a comprehensive subjective evaluation of a textile based on tactile feelings induced by physical stimulation from the mechanical properties of the material (Raheel & Liu, 1991), this definition was the basis for following studies that aimed to define the mechanical properties of textile and the corresponding human response and perception in order to create standardized evaluations. The definition of sensory comfort today include thermo-physiological comfort, sensorial comfort, body movement comfort and aesthetic appeal (Wong, 2006). However, this definition still does not account for the personal comfort threshold variations between people and their perceived comfort which can only be understood using subjective evaluations (Barker, 2002).

Based on the complexity of the definition of clothing comfort, research has mainly focused on fabric properties and pressure sensations (including other sensory definitions such as itchiness, softness, roughness... etc.) as significant attributes to clothing comfort that are sometimes combined with physical activity in order to study the affect of sweating and heating on the body (Bell et al., 2003; Cardello et al., 2003; J. Li et al., 2012; Wong, 2006). One such study was conducted by Barker et al. (2002) on hospital gowns for periods of activity and rest, subjects sensed qualities of bending stiffness, shear stiffness and surface roughness during periods of little activity (cool environment), while qualities of skin contact and fabric cling were sensed during physical activities (warm and humid environment).

In another study, the relationship between pressure and comfort was examined by Jin et al (2008) on one hundred subjects using tight seamless sportswear, in controlled average temperatures (23

± 2ºC and humidity of 68 ± 5%). The volunteers were asked to wear four different types of sportswear and to performs certain exercises. The pressure on several key point areas was measured using a balloon type sensor and the values obtained were associated with pressure comfort sensation of the participant. The dynamic comfort pressure range for each part of the body is summarized in Table 4-1 (Jin et al., 2008).

Table 4-1: Comfort pressure range values on different parts of the body (Jin et al., 2008)

| Parts | Comfort Pressure (KPa) | Parts | Comfort Pressure (KPa) |
|---|---|---|---|
| Arm | 0.572~0.832 | Waist | 0.374~0.554 |
| Shoulder | 0.513~0.896 | Abdomen | 0.142~0.811 |
| Breast | 0.130~0.444 | Hip | 0.744~1.463 |
| Back | 0.301~0.699 | Thigh | 0.331~0.892 |
| Upper side | 0.131~0.308 | Under outside | 0.321~0.721 |

According to Jin et al. findings, comfort pressure of a tight fit clothing ranges from 0.13 to 1.463 KPa and varies based on the anatomical part of the body, however, comfort pressure range on the head was not identified so far.

Taking into consideration the broader meaning of comfort, it is important to acknowledge the necessity of good ventilation and possibility of absorbing sweat as well as softness as attributes that can be lead to comfortable cap, as long as hygienic concerns related to possibility to clean or even sanitize are met. On the other hand, the psychological aspect when it comes to perceived comfort is far more challenging, as the wires and optodes sticking out of the head are not considered reassuring or comforting in general. Therefore, attempts of creating wireless and smaller optodes are not only beneficial in reducing movement artifacts and noise, but would also reflect positively for the person wearing the cap. In this study only comfort related to pressure values induced by the cap are considered.

### 4.1.2 Identifying the Comfort Pressure Range on the Head

In order to quantify the comfort range of pressure on the head as well as define the pressure threshold necessary to establish stable optode contact, a dynamic pressure sensor monitoring circuit was designed and added to the NIRS/EEG system of the Imaginc group (Lareau et al., 2011; Le Lan, 2013), using this circuit up to three contact pressure sensors (B201-L sensors from

Tekscan) can be used to monitor the pressure simultaneously during NIRS monitoring. The circuit can also be used independently to measure the dynamic contact pressure solely. The sensors were calibrated using incremental weight of 100 g in order to define their active range. Figure 4-1 illustrates the sensor response curves compared to each other. As shown, sensors 1 and 2 can be used interchangeably, however values registered using sensor 3 need to be calculated separately. The sensors seem to saturate at values approaching 800 Pa with a slightly higher curve for sensor 3. More details on the calibration of the sensors is shown in Appendix B.

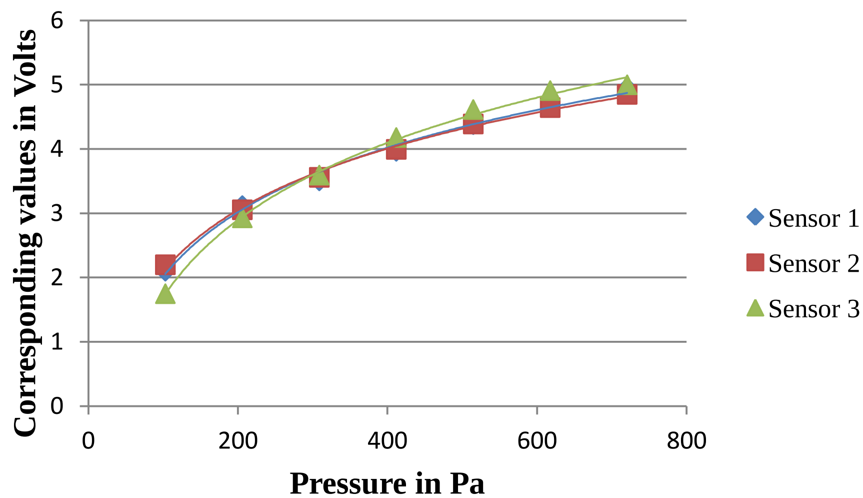
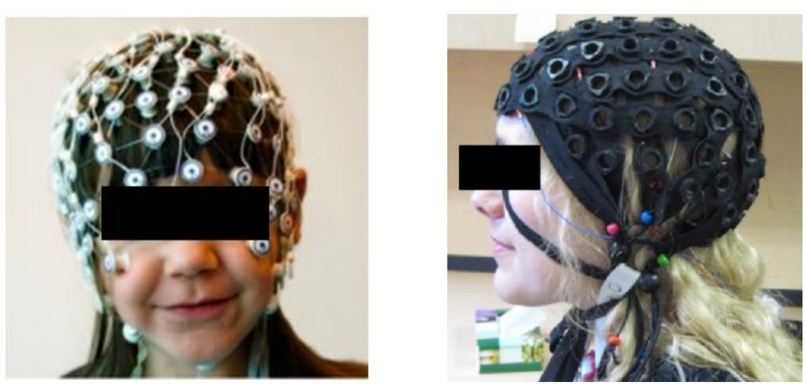



Figure 4-1: Active pressure range for the three sensors

The designed sensor system was used to measure the pressure induced on the head with two caps: a commercial EEG elastic band cap, *HydroCel GSN130 EGI*, and the elastic cap designed by our group for use with epilepsy patients. Figure 4-2 shows the two caps used.



(a) (b)

Figure 4-2: Caps used to identify contact pressure value induced on the head: a) HydroCel GSN130 EGI elastic band EEG cap, b) Elastic band cap developed by the Imaginc group.

The two caps share a similar concept in that the tight fit induced by the elastic band causes an increased amount of pressure on the head and stabilizes the optodes. In general, more pressure is sensed on the forehead without the cushioning effect that hair provides in other parts of the head.

In each case the pressure values were measured over two phases: a static phase, where the person wearing the cap sits still without moving the head, and a dynamic phase, where the person starts rotating the head in different directions, up down and sideways. The pressure values were not registered for a person in full motion.

<u>EEG cap pressure (the cap model from HydroCel GSN130 EGI) very tight fit : </u>The pressure sensors were placed under the EEG electrodes at the frontal, prefrontal and temporal areas. Using three sensors at different locations the dynamic pressure values associated with each sensor are shown in Figure 4-3.

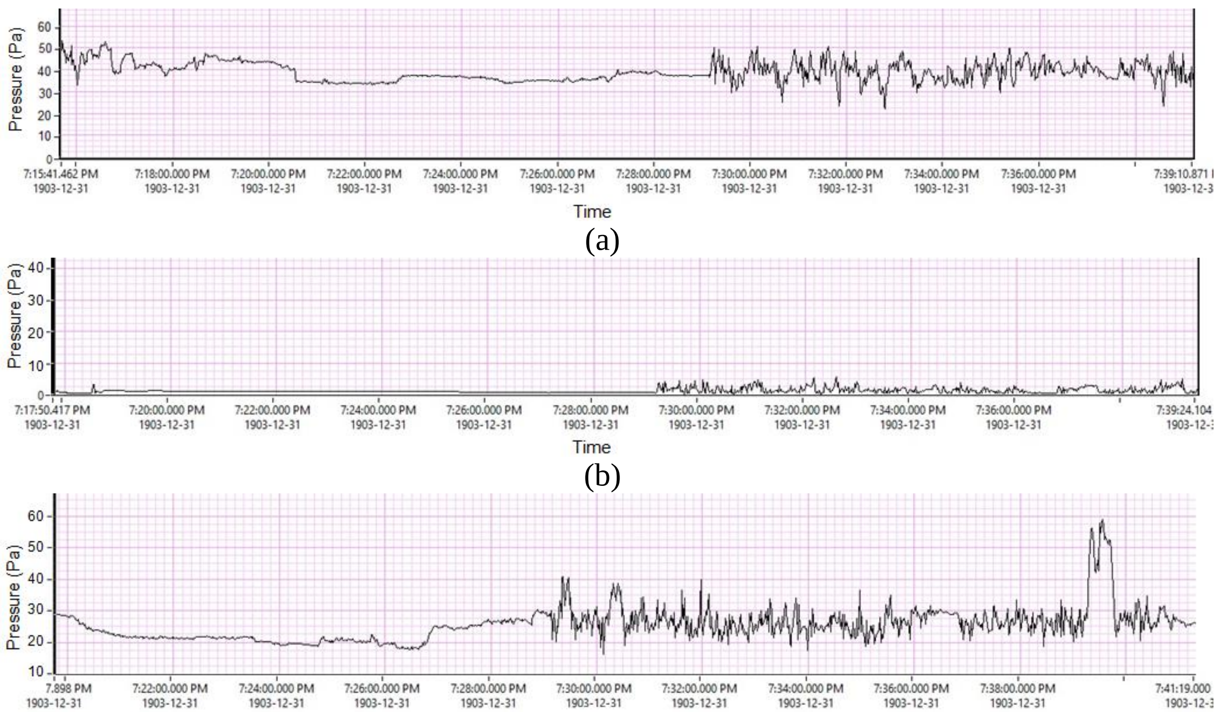



Figure 4-3: Contact pressure fluctuation over time using a commercial EEG cap (<u>*HydroCel GSN130 EGI*), </u>The graph shows both the static phase with minor fluctuation and the dynamic phase for a person moving and rotating his/her head: (a) Data from sensor 1, (b) data from sensor 2, (c) Data from sensor 3

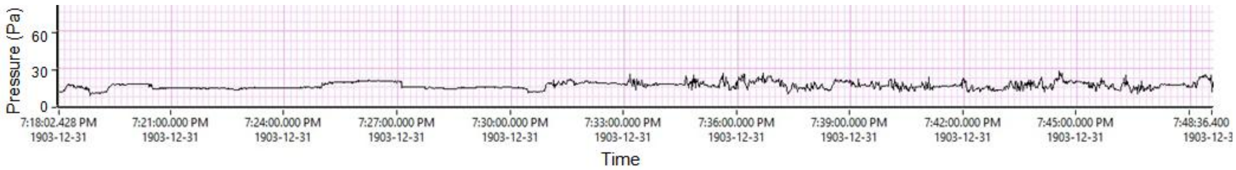
The sensors clearly captured the effect of moving the head on the pressure induced by the cap, causing pressure fluctuations with high pressure peaks, this demonstrates why tight head monitoring caps can become increasingly uncomfortable with fully moving patients versus stationary ones. The pressure values illustrated in Figure 4-3 were translated into the values summarized in Table 4-2. Table 4-2: Average pressure values induced using (*HydroCel GSN130 EGI)* EEG cap

| **Sensor** | **Average Static Pressure (Pa)** | **Average Dynamic Pressure (Pa)** | **Peak values (Pascal)** |
|---|---|---|---|
| 1 | 35 | 40 | 50 |
| 2 | ~3 | ~5 | 6 |
| 3 | 20 | 28 | 60 |

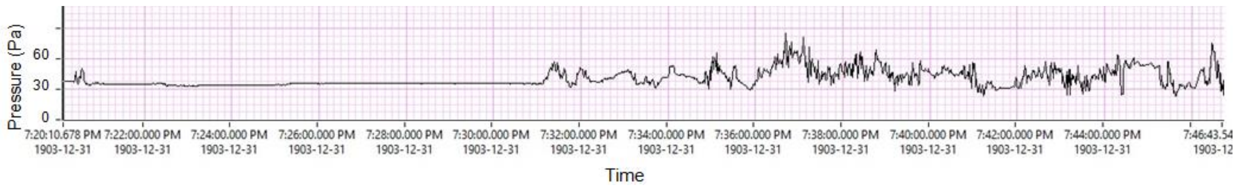
These values were calculated by first establishing the voltage corresponding with the average pressure illustrated in the static and dynamic phases as well as the peak pressure registered at the dynamic phase. The voltage values then were traced to their corresponding pressure values using the sensor calibration curves shown in Figure 4.1, and in more detail in Appendix B.

Elastic cap used by the Imaginc group for epilepsy studies (tight fit) : The pressure sensors were placed under the NIRS optodes at the frontal, prefrontal and temporal areas. The values obtained are shown in Figure 4-4. In general, the elastic cap exhibits a more uniform pressure distribution across the measured areas, which may translate to more comfort.

Also, pressure fluctuations during head movement are not only associated with the amount of pressure induced originally by the optode, they also reflect the effect of a specific movement on that particular cranial area. However, given head shape variations between different people and the limitation of the number of available optodes, which makes monitoring more than three locations at one session unattainable, it was not possible to assess the exact effect of a particular movement on pressure fluctuations in every cranial zone.




(a)

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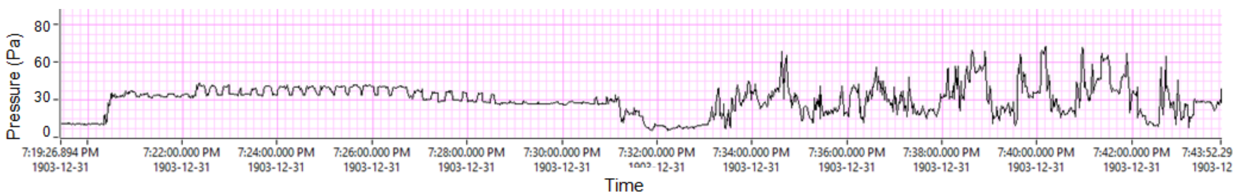



(c)

Figure 4-4: Contact pressure fluctuation over time using the Imaginc group elastic band cap. The graph shows both the static phase with minor fluctuation and the dynamic phase for a person rotating his/her head: (a)Data from sensor 1, (b) Data from sensor 2 (c) Data from sensor 3

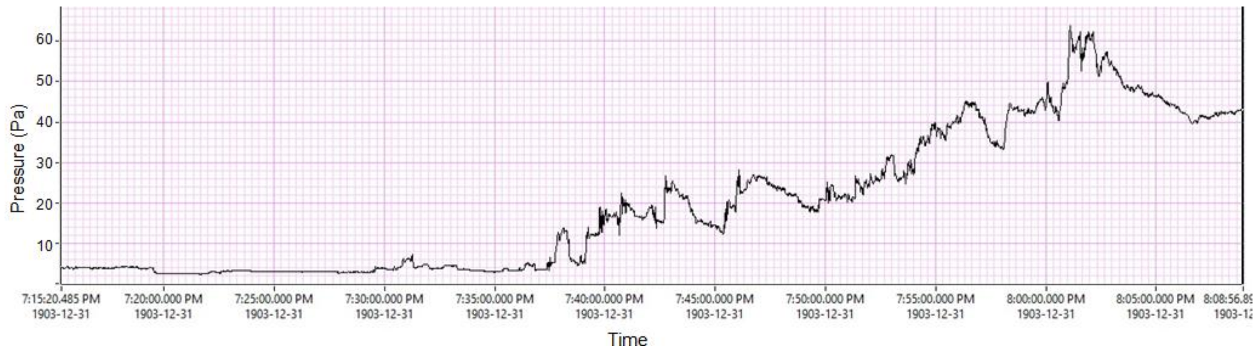
The pressure obtained during this monitoring sessions were translated into values shown in Table 4-3 using the same methodology explained for the EEG elastic cap.

Table 4-3: Average pressure values induced using the Imaginc group elastic band cap

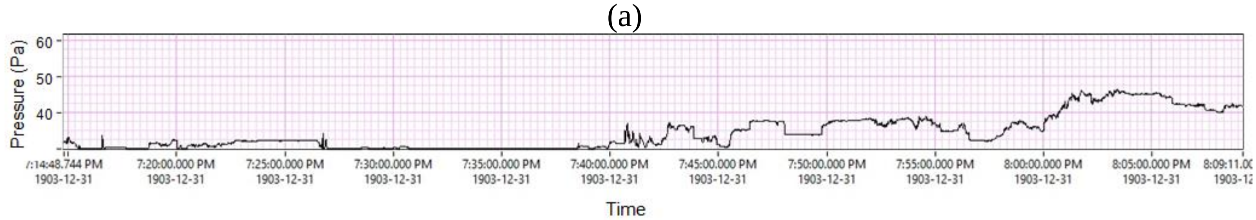
| **Sensor** | **Average Static Pressure (Pa)** | **Average Dynamic Pressure (Pa)** | **Peak values (Pascal)** |
|---|---|---|---|
| 1 | 20 | 20 | 30 |
| 2 | 30 | 35 | 40 |
| 3 | 40 | 40 | 60 |

Based on these results, it was observed that satisfactory brain imaging contact was established with optode pressure values ranging from 30-40 Pa, which can be designated as the "stability" pressure range necessary for brain imaging.

On the other hand, in order to identify the comfort pressure range on the head a tight fit head-band equipped with an inflatable balloon was used. One of the sensors was placed directly under the balloon, while the other two sensors were placed on the sides of the forehead. The pressure values were registered for the tight fit head-band as the balloon was gradually inflated underneath, increasing the pressure. The results are shown in Figure 4-5




(a)

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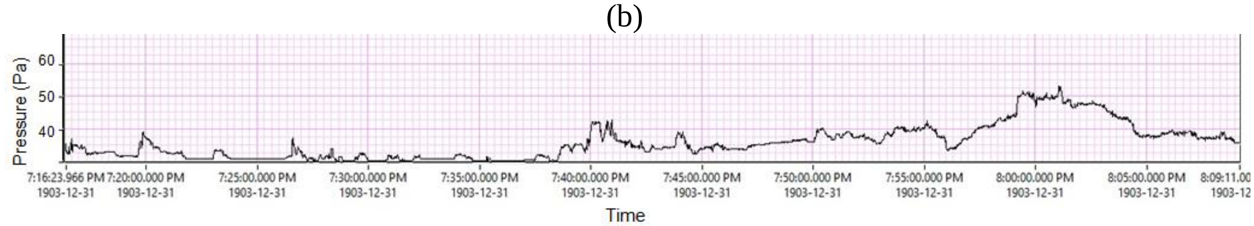



(c)

Figure 4-5: Contact pressure values of a tight fit head band with an inflatable balloon: (a) Data from sensor 1 directly under the inflating balloon in the middle of the forehead, (b) Data from sensor 2 on the prefrontal area to the left of the balloon , (c) Data from sensor 3 on the prefrontal area to the right of the balloon

This study shows that the pressure induced by the headband becomes uncomfortable at 65 Pa and above, it also showcases a very common situation in tight headwear associated discomfort, that can be also due to head shape variations, where localized pressure values may rise to uncomfortable levels with minimal effect on the rest of the head. Sensor 1, which was placed directly under the inflating balloon, captured the peak pressure value which corresponds to ~65 Pa, while the increase in the two surrounding locations are within the range of 40-50 Pa.

### 4.1.3 Discussion

Based on these measurements, the comfort contact pressure range on the head is far lower than values reported in previous studies for other anatomical parts, with an average of 40-60Pa on the head using tight fit headwear compared to 0.13 to 1.463 kPa reported by Jin et al. (2008) on other parts of the body. This statement however needs to be confirmed by using the same device to measure pressure values at different parts of the body, and can only be generalized based on measurements conducted on a large group of participants (~30), such a study is currently ongoing in our group, for more details please refer to Appendix C.

Considering that the pressure necessary to stabilize the optodes ranges from 30-40 Pa. while the pressure comfort margin is ~50 Pa, it is obvious that achieving NIRS cap stability as well as comfort can be a very challenging task. Balancing the two concepts requires active monitoring of pressure distribution throughout the cap, with the possibility of adjusting this pressure value in order to contain it within this very specific range. On the other hand, pressure balancing may be possible using passive gripping mechanisms that rely on molding the cap to fit various head shapes.

Sources of error in this experiment include:

1. Loss of contact with the sensors: Since the pressure sensors were placed underneath the EEG electrodes/NIRS optodes, contact with these elements may fluctuate with movement leading to temporary partial contact or loss of contact with the sensors. This may lead to false pressure fluctuation values.

2. Effect of hair underneath the optodes: Hair acts as a spring or a cushioning mechanism affecting the pressure values registered particularly at low-pressure ranges (<30 Pa). This may partially account for the higher pressure fluctuation values encountered at low pressures, while the values become more stable as the pressure increases. In order to minimize the effect of hair, before placing the pressure sensor hair was tossing from underneath the optodes, however their effect may be present during movement.

3. Precision of pressure sensor: Given that the active range of the pressure sensor was from zero to approximately 600 Pa, with a higher error value at the lower end of this range

(data shown in Appendix B), the results obtained need to be confirmed using modified pressure sensors with an active range from zero to ~200 Pa.

## 4.2 A Comparative Look at the stability of existing NIRS caps

Of the various caps that were developed during the course of the project based on commercial NIRS and EEG cap designs, three caps that are presently being used in NIRS signal acquisition were tested under three distinct conditions: rest, moving the head and walking. The testing was performed using the NIRS/EEG system of the Imaginc group, on a single right handed participant.

### 4.2.1 Experimental procedure

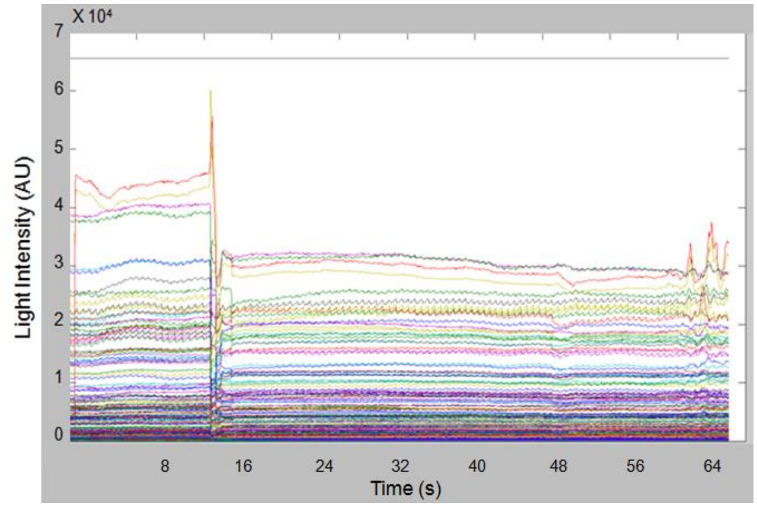
In the three cases, the full number of emitters and detectors were used (16 detectors and 16 emitters) to cover the frontal and prefrontal lobe. The Velcro cap had a higher spatial resolution as the distance between emitter/emitter and detector/detector were 2.5 ±0.2cm, while the distance between emitter/detector were 3.0 ±0.2cm. As for the neoprene and the elastic band cap, the optodes locations were equidistant at 3.0 ±0.2cm.

The same volunteer was tested with the three NIRS caps shown in Table 4-4. Once the cap was installed, the n-back test was performed (Kirchner, 1958) for n=2, where a series of numbers were recited with an interval of ~3 sec between each number, the participant had to recount the second previous number of the series under three conditions: sitting, moving the head and walking. Each task lasted a minute, and notes pertaining for each cap were made with regards to how comfortable it was on the head.

The participant was right handed, in his twenties and had a large head (circumference of 58 cm), with short dark hair and large forehead. All the caps were stabilized with an attachment to a belt under the arms.

### 4.2.2 Results

Based on the feedback from the participant, the neoprene cap was uncomfortable, while the other two caps did not cause any particular discomfort. The results obtained in each case are shown in Figures 4-6, 4-7 and 4-8.

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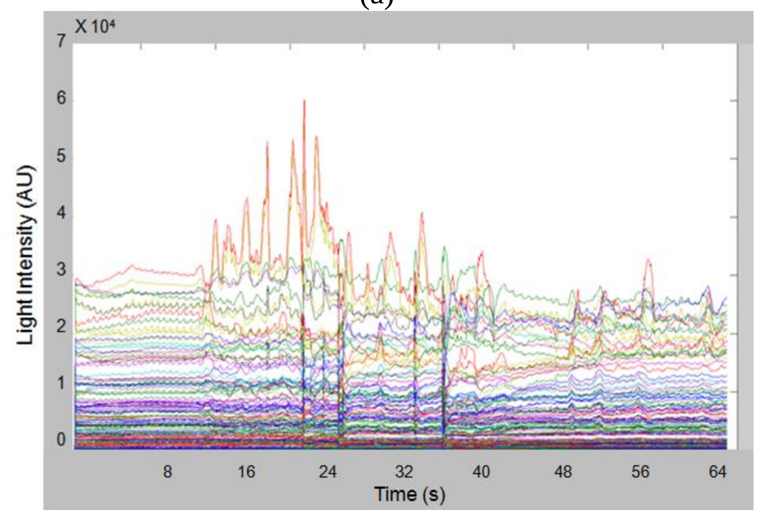
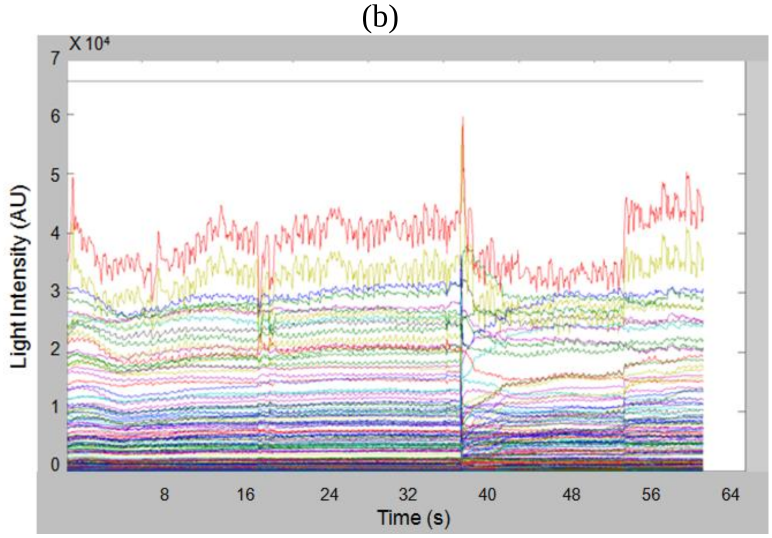
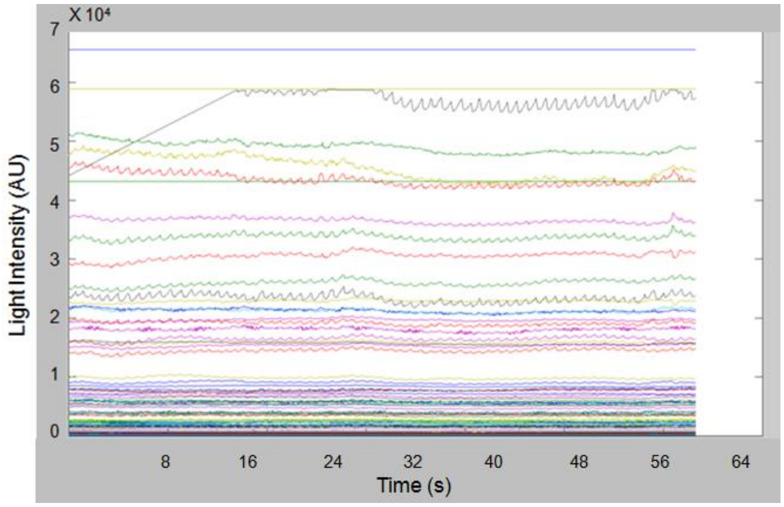



(b)

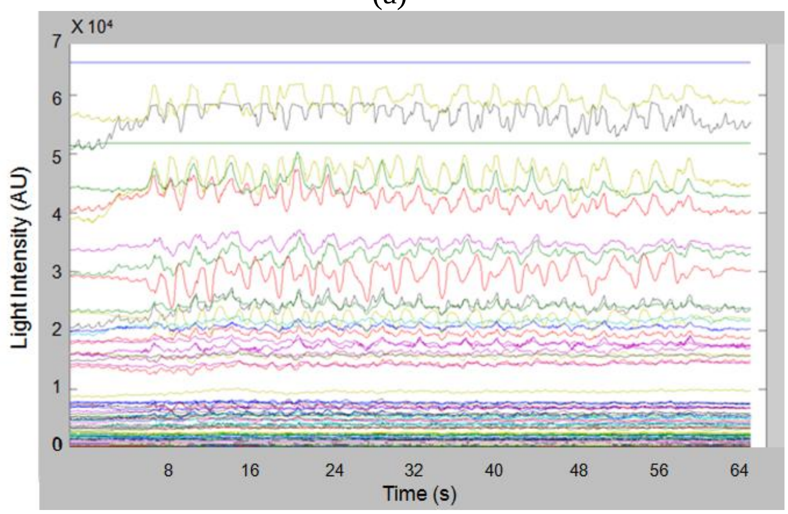



(c)

Figure 4-6. NIRS signal measured with Velcro cap: (a) while sitting motionless, (b) Moving the head up/down, and right/left, and (c) Walking slowly




(a)

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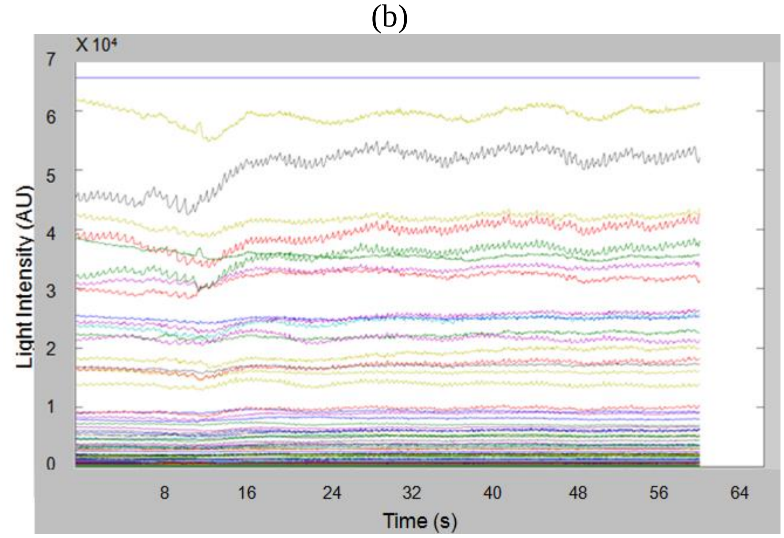
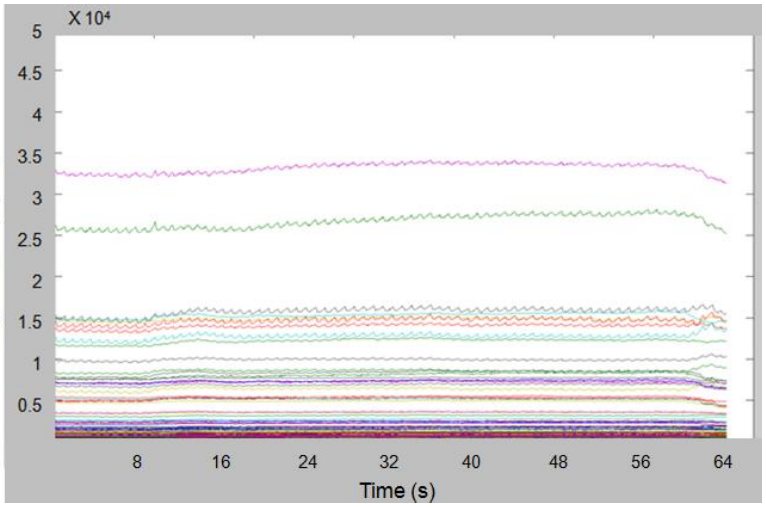
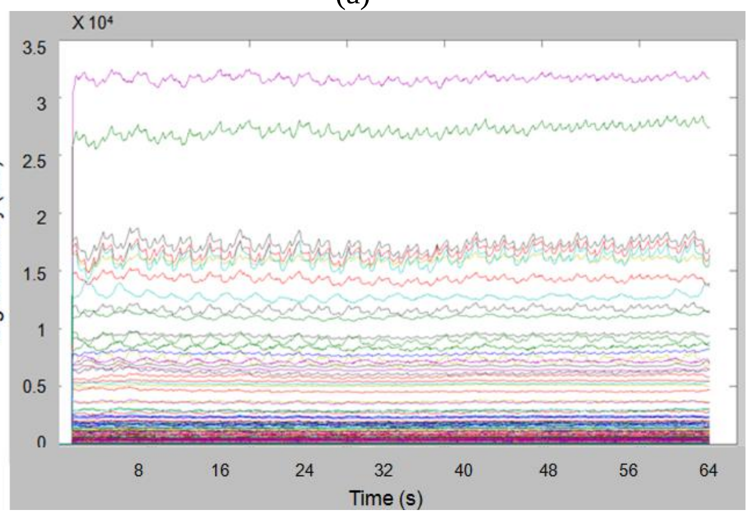



(c)

Figure 4-7. NIRS signal measured with elastic band cap: (a) while sitting motionless, (b) Moving the head up/down, and right/left, and (c) Walking slowly




(a)

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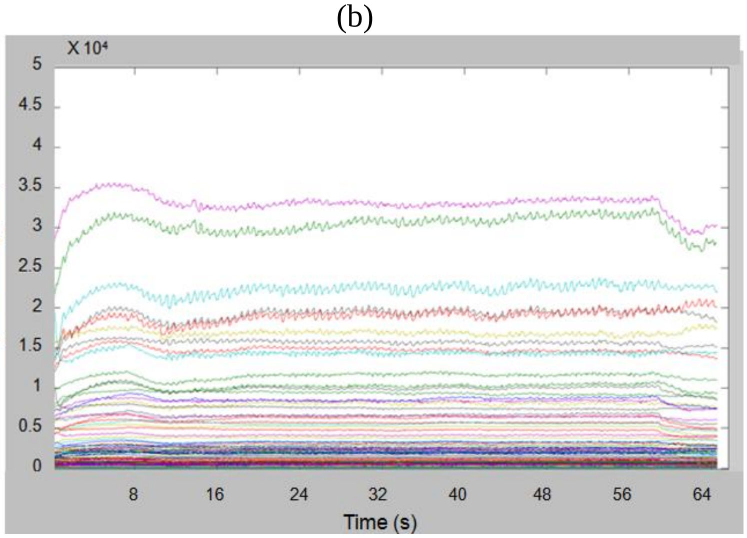



(c)

Figure 4-8. NIRS signal measured with neoprene cap: (a) while sitting motionless, (b) Moving the head up/down, and right/left, and (c) Walking slowly

Table 4-4 shows the three caps as well as the number of rejected channels in each case. These channels were rejected based on the illumination data collected, in case these channels were saturated or not enough light was detected.

Table 4-4: The number of rejected channels in each case

| | Velcro cap | Elastic band cap | Neoprene cap |
|---|---|---|---|
| Sitting | 69 | 130 | 140 |
| Head movement | 74 | 138 | 146 |
| Walking | 73 | 135 | 143 |

In general the number of channels rejected increased with head movement and to a lesser degree by walking compared with the static phase. This is mostly due to localized optode inclinations or hair displacement which may cover some of the optodes and lower the amount of light detected. These experiments provide sufficient preliminary results to identify the issues related with different cap types.

### 4.2.3 Discussion

The n-back is a known cognitive test to measure the working memory. It was introduced by (Kirchner, 1958), and is known to activate the prefrontal cortex (T. Li et al., 2010), however since this test was coupled with other motor tasks, such as gait and head movement, a larger area was monitored to include the frontal zone. Isolating a hemodynamic signal using NIRS for the n-back test requires a large number of participants over extended periods of time, such a study is currently ongoing in the EPIC center with one of our collaborators. However, the experimental procedure described herein does not aim to identify the hemodynamic signals associated with this particular task, especially considering the variations caused by adding the motor tasks in each case. This setting is only interested in evaluating the effect of movement artifacts on the registered NIRS signal using each cap.

Identifying artifacts in NIRS is the subject of several studies (Fekete et al., 2011; Kim et al., 2011; F Scholkmann et al., 2010). Generally, large spikes in the signal is considered a movement artifact as shown in Figure 4-7.

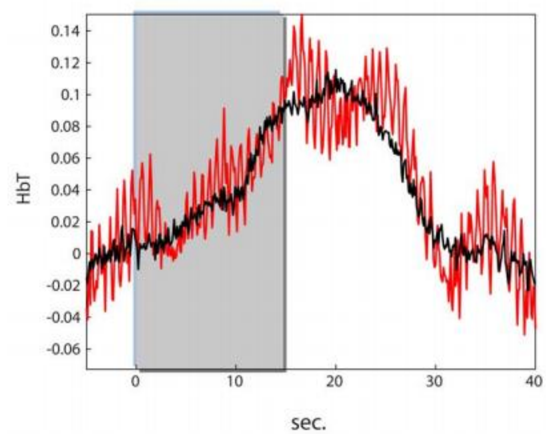



Figure 4-9: The NIRS signal before (in red) and after (in black) the removal of movement artifacts. (Fekete et al., 2011)

Therefore, the collected signals were evaluated solely on the amount of disturbance registered in each case compared to the static (control) condition where the subject was not in motion. Based on this analysis, it is obvious that factors influencing movement artifacts are more than the type of the cap, and the task required. Most importantly, the degree of pressure a particular cap imposes on the head represents the single most important factor in reducing movement artifacts, regardless of the type of the cap used.

The neoprene cap which was largely considered the least stable cap throughout this study, based on the feedback from several collaborators, registered the lowest amount of movement artifacts as well as change in the number of rejected channels with movement. This was due to the fact that it was clearly uncomfortable, specially on the prefrontal zone, where it exhibited excessive pressure on the participant's head.

On the other hand, the elastic band cap exhibited uniform and balanced movement artifacts which reflects the equally distributed pressure throughout, versus the Velcro cap which is currently used with gait studies for an n-back procedure.

In general, head movement was the task that instigated larger movement artifacts compared to walking, which may be very important considering that movement artifact related to full body motion, either linear or angular acceleration, can be filtered out by adding an accelerometer (Iramina et al., 2010; Virtanen et al., 2011). However, movement artifacts related to head movement cannot be singled out and eliminated easily, which is the reason why all NIRS studies rely on carefully designed and controlled test sessions that try to minimize or eliminate head and jaw movement.

Unfortunately, this small comparative look at the performance of the three caps cannot be used to gather any quantitative in depth data on the quality of the NIRS signal itself, especially due to the discrepancies between the optode locations with each cap and the different spatial resolutions. Such a study would require a larger number of participants (≥10) in order to account for the effect of head shape variations, as well as define the hemodynamic signal and isolate the differences associated with the cap material and design. The n-back test itself may not be considered the most suitable for future cap evaluation tests, as it is generally hard to detect and isolate. However, general assessment of the efficiency of each cap in this study is largely based on the feedback from several collaborators over the duration of the master thesis, who are employing some of these designs in their current research. Based on individual tests that were performed on each cap, the elastic band cap was found to be the best suited for a full head covering cap used with epilepsy patients, while the Velcro cap is used with the n-back test coupled with gait.

Sources of error in this experiment include:

1. Hemodynamic variations during movement can escalate due to increased motor tasks and extracortical hemodynamic activity. However, since this is only a comparative study between each case, the signal variation between comparable motor tasks for the three caps studied were considered in addition to the basic comparison between the motor and static case with each cap.

2. The spatial distribution of the optodes was not analogous in each case, as the Velcro cap provides a denser optode distribution that is focused on the frontal and prefrontal areas, versus the more loosely distributed optodes, with the 3 cm equidistant design of the neoprene and the elastic band cap. This is less significant in a study that does not seek to

single out hemodynamic signals of the task performed, however it is still to be considered as a source of possible data variation, that may account for the disparity in the number of rejected channels in each case, particularly since a certain number of optodes in the neoprene and elastic band cap covered the parietal zone as well as the frontal zone

3. Since this study relies on a single participant, therefore it cannot be used as an evaluation for the performance and advantages of each cap, particularly since pressure plays such an important role in reducing the amount of movement artifacts. In order to successfully evaluate the performance of each design, a large group of participants with varying ethnic backgrounds have to be included. On the other hand, the study has to incorporate full head NIRS signal monitoring for a variation of cognitive and motor tasks in order to evaluate the performance of each cap for various cranial zones.

Future cap evaluation tests may be standardized by proposing a series of cognitive and motor tests for the entire cranial zone that the cap covers with a large group of participants (at least 10, preferably of different ethnicities). Thereby, eliminating the effect of localized pressure on cap stability assessment. However, based on this experimental results it is obvious that available portable NIRS caps, even with the aid of cap stabilizing attachments, can provide only sufficient support for short term, carefully controlled experiments, such as gait, cognitive tasks and even a short outdoor bicycle ride. However, for a fully moving subject, that may engage in head movements, various body manoeuvres that are not controlled or planned during the course of the daily activity, the stability of these caps is challenged. Therefore, other cap stabilizing methods have to be studied in order to meet the requirements of this upcoming application.

Since there are no materials that combine conformability and non-flexibility, a different approach to the NIRS cap design was required. In this regard, the use of non flexible tissue coupled with a fluid that can fill in the head variation gap was suggested as a closer step towards the required NIRS cap design. On the other hand, equal pressure distribution on the scalp in order to ensure good quality optode contact and stability is analogous to the concept of a "grip" in robotics. Robotic grippers have been extensively studied in order to accommodate various gripping requirements. Chapter five is dedicated to the "intelligent cap" designs that address the need for more elaborate future solutions for portable NIRS systems, based on robotic grasping principles.

# CHAPTER 5

# THE DEVELOPMENT OF A LONG-TERM NIRS CAP

## 5.1 Achieving the needed NIRS grip

The study presented in the previous chapters outlines several previously unidentified parameters and conditions that the NIRS cap has to provide in order to meet the requirements of future NIRS imaging systems. It also provides ample evidence that present cap designs are unable to sustain scalp contact in freely moving studies, even with the help of additional cap stabilizing methods such as the connection with the belt under the arms. Therefore, the need for better cap designs that are capable of adjusting with various head shapes in addition to providing a controlled and uniform pressure throughout emerges as a necessary step in discussing the future of this technology.

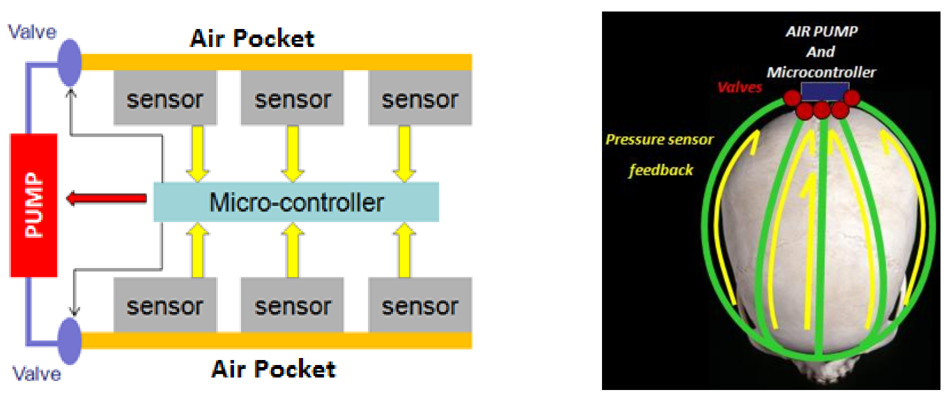
As mentioned in Chapter 2, achieving a tight grip is not a new concept in robotics, rather it is a very well established field. The major difference however between traditional gripping studies in robotics and the requirements of a NIRS system lies in the fact that robotic grippers focus on the forces affecting the general conditions of the gripped object rather than the localized conditions at every single location of the gripped surface. The closest examples that can be adopted in this application are those that rely on cushioning as well as gripping, in a manner that utilizes a power grip that engulfs the object rather than stabilizes it using a set number of point forces.

Within this context two types of grippers are of interest, both rely on pneumatic force as a working fluid to provide the necessary molding/cushioning and create a uniform pressure value throughout. Taking into consideration head shape variations, the only alternative to a system that relies on excessive pressure on one part of the scalp in order to provide basic pressure on other parts of the head is a system that can fill in the gaps in areas that lack contact while maintaining the same contact conditions in other areas. This can be provided by either inflating air pockets in areas that lack contact, or on the other hand, by designing a mouldable caps that can modify itself and once uniform contact is applied it solidifies to create a non-flexible interface. There are however inherent differences between the two concepts as they provide different sets of advantages and shortcomings. Both of these concepts will be discussed in detail in the following sections.

## 5.2 Inflatable cap design

Similar to the work presented by Choi et al. (H. Choi & Koc, 2006), the concept of providing an inflatable system can provide friction in order to decrease the need for directional force is very interesting for NIRS cap designs, particularly since it creates an engulfing mechanism that is necessary to establish contact at every location on the head. However, the most important difference between this robotic gripper and the NIRS cap, is that the gripping mechanism itself is provided by the mechanical jaws, not the inflatable balloons. On the other hand, inflatable systems need to be monitored in order to ensure that no excess pressure is applied on certain areas, and to regulate the amount of air needed to establish the required pressure.

Such a design can be made by creating a fixed outer shell for the cap, using non-stretchable light fabric in addition to a stretchable inner layer. The cap has to be divided to several distinct air pockets identifying cranial zones that vary from one head shape to another. The amount of pressure inside the air pocket can then be adjusted based on a feedback signal obtained from contact sensors distributed on the surface of the inflatable pocket using a "branch" system, where each branch of sensors is related to a single balloon that is regulated by a micro-valve. The sensors feedback provides the necessary information to a microcontroller that responds by opening or closing the micro-valve allowing air into that air pocket. The microcontroller also regulates the micro-pump action by turning it off once all micro-valves are closed. The basic architecture of this system is shown in Figure 5-1.




(a) (b)

Figure 5-1. Inflatable cap design, (a) Air pockets, lined up with contact sensors provide a feedback loop to control the valves and the air pump via a microcontroller, (b) The distribution of the electronic components, and the inflatable air pockets (in green) as well as the feedback pressure sensors (in yellow) on the cap

This division is essential since uniform inflation of the cap may lead to increased pressure at certain location while other areas lack the pressure necessary to establish good contact quality. Once all pressure sensors return a positive contact signal, all air pocket valves are closed then the air pump is turned off. This system is analogous to robotic fingers that are controlled separately based on the sensorial feedback from each finger.

Taking into consideration that the NIRS cap is highly perforated with several optode locations, this solution adds another layer of complexity and cost to the design in order to provide the necessary sensors, micro-valves, microcontroller and micro-pump onto the cap. Therefore, such an endeavour may be considered if these components (the micro-pump, micro-valves and sensors) were specifically designed for the clinical imaging cap using flexible electronic manufacturing methods that are lightweight and can conform with the material of the cap, or if these components were made small enough to be portable on the head for the duration of the imaging process.

On the other hand, the circuitry and complexity of such a design may be justified if it was able to incorporate additional functions such as an imbedded accelerometer, power and data transmission unit that allows for a wireless optode and sensor data transmission directly from the cap into a processing device without the need for any connecting wires. Most importantly, the ability to provide dynamic contact pressure data combined with the accelerometer and optode imaging information may be used to create a complete signal processing and filtration system, thus providing a comprehensive data analysis that is essential for freely moving cases.

A NIRS cap with these specifications can no longer be regarded as an accessory, rather as an integral part of the electronic system, and must be studied as such.

## 5.3 Universal vacuum gripper

Given the complexity of a sensor based NIRS cap, a look at other pneumatic solutions for a simpler design that may achieve this project's objectives is warranted. Much like the passive universal gripper that was a breakthrough in robotics as a simple and effective method to handle sensitive grasping operations, a similar approach may produce the desired goal without the need for advanced electronics or complex manufacturing methods. As mentioned in Chapter 2, the study made by Brown et al. (Brown et al., 2010) established some of the basic parameters identifying the gripping force in the universal gripper, these include the type of gripped surface (smooth or rough) as well as the enveloping angle. The enveloping angle in a NIRS cap is $> \pi/2$, (Figure 2-10) which compensates for the fact that the gripped surface (the head) is not smooth in most cases due to hair type variations. However, the effect of a perforated gripper, due to the 3 cm equidistant optode locations, was not studied previously.

Universal grippers rely on the ability of the balloon to mold itself around an object and to lock that shape once air is evacuated in order to create a firm grip. This molding mechanism does not rely on pressure in maintaining hold of the object, which makes it safe enough to transport raw eggs, and it is simple enough to be incorporated easily into existing NIRS systems without the need for sophisticated electronic circuitry or micromachining. Therefore, attempts at creating a full head covering cap using a custom made balloon was initiated in this study.

The most prominent obstacle in creating a vacuum NIRS cap was the ability to create an airtight structure in a highly perforated accessory. Ideally, a single head shaped balloon with equidistant 3 cm holes is needed to provide a successful prototype for this concept. However, based on the manufacturing procedure of balloons, such a design requires a sophisticated two-part mold to be fabricated, after which liquid latex has to be poured inside the mold to create the balloon.

Given that balloon manufacturing is generally conducted in big standardized factories, attempts at contacting one to fabricate a prototype were not successful, in addition to the difficulty in obtaining the necessary material to create a balloon in-house, such as pure latex. Alternate solutions were based on either using tube balloons filled with coffee grains (which was used in the study of Brown et al.) sewed on the inside of a regular cap, or conversely, making an air-tight cap by using regular tissue covered with liquid latex, or using latex sheets.

### 5.3.1 Construction of a vacuum cap using tube balloons

Given that the distance between each optode location is 3 cm, and that the diameter of optodes used is ~1cm which leaves less than 2 cm distance between each socket; therefore, the use of tube balloons that are ~1.5 cm in diameter not only provides an airtight structure, but it also fits the available inter-optode space.

The first attempt at creating a full head covering vacuum cap using tube balloons was made by lining up a regular NIRS cap with tube balloons filled with coffee grains, as shown in Figure 5-2.

Each balloon was sealed with an O-ring fitted with coffee filter in order to seal the coffee grains inside the balloon. As shown, only the periphery of the cap was lined up with tube balloons in response to the finding reported by Brown et al. (2010) that identified the importance of the peripheral seal in establishing the suction force necessary for the grip stability. However, after testing the cap it was concluded that the entire cap has to be lined up with tube balloons in order to increase the contact area and to stabilize the optodes at various locations. However, increasing the number of tube balloons created a connection issue with the vacuum pump.

(a) (b)

Figure 5-2. A regular cap lined with tube balloons : (a) The positioning of the tube balloons on the cap, (b) The shape of tube balloons used and the filtration ring that secures the granular material inside the balloon during air pumping

In another model, an attempt to create a perforated cap using tube balloons was made. Much like the elastic band cap, this balloon is meant to provide head ventilation, in addition to easier hair clearing access. This design is shown in Figure 5-3.

(a) (b)

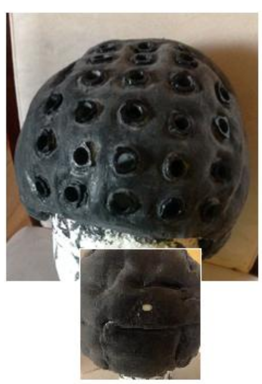
Figure 5-3. Velcro bands lined with tube balloons: (a) General distribution of the balloons and optodes, (b) The special socket design in order to increase the stability of the optode

This model required a special socket design in order to increase the connection between each strip. In general it was successful in providing the necessary vacuum to create a grip on the head.

### 5.3.2 Air tight whole head covering cap

Two methods were used to fabricate a full head covering cap: regular tissue cap sealed with liquid latex and latex sheets glued together with a special glue. In general, the fabrication process for a full head covering cap was quite laborious, particularly since the optode distances were so small that any errors in joining the two layered tissue led to either loss of air sealing properties or conversely loss of available space to fill with granular material.

The regular tissue cap fabrication process consisted of making two separate layers of tissue: an outer layer from nonflexible material, and an inner layer from extendable material. The process of making holes inside the cap for the frontal area only relied on identifying each position sequentially in order to allow for an extra width from the inner material to be maintained to provide the necessary space for stuffing. Once the optode locations were identified and the periphery was sewed, the holes were cut out and the cap was stuffed using foam ball grains, as shown in Figure 5-4. The cap was then painted several coats (in perpendicular directions) of liquid latex on the outer and the inner surfaces. The sockets corresponding to the Imaginc group optodes were then glued in and the surrounding latex had to be cleared using a razor in order to make sure that the optode would fit at these locations.



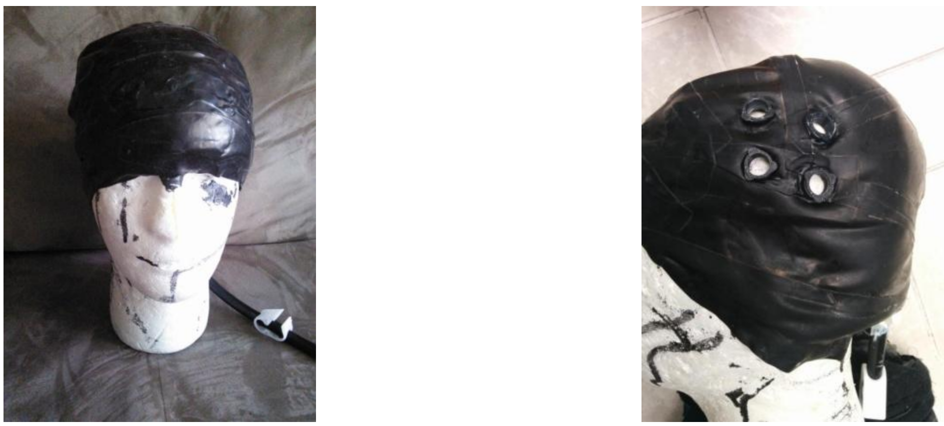
(a)

(b)

Figure 5-4. (a) Textile cap covered with liquid latex and fitted sockets, (b) the granular foam balls used in stuffing the cap and the portable vacuum pump used to evacuate the air

In order to be able to create vacuum conditions the cap was fitted with a vacuum sealer bag opening, shown in Figure 5-4a. The design was not successful however, as it failed to provide air tight sealing conditions necessary to drop the pressure inside the cap. This is mostly due to the various openings and creases that were not equipped to handle vacuum tight conditions.

The latex sheet cap, on the other hand, was able to provide the necessary air-tight properties. This design is shown in Figure 5-5, In this model also two types of latex sheets were used, a 0.4 mm thick latex sheet at the outer surface versus 0.25 mm sheet on the inner surface. Thus, changes on the inner surface were more dominant over changes in the outer surface.



(a) (b)

Figure 5-5. (a) Latex sheet whole head covering cap, (b) The four socket openings that were used to test the cap stability

In this model only four socket openings were made in order to demonstrate the effect of vacuum on optodes stability, this was also challenging as it compromised the air-tightness property of the cap, making it loose its rigidity as the vacuum suction stops.

### 5.3.3 Results obtained with the vacuum cap model

Preliminary tests using the vacuum cap were promising. The caps were not able to maintain the vacuum condition over long time which made regular NIRS testing using these models not possible with the present solutions. However, over the short duration where vacuum was maintained, the sockets were rigidly fixated at the scalp and attempts at manually displace them were not successful under these conditions. There are several observations regarding this system that can be summarized in the following points:

1. Since there is no mechanical part enforcing pressure on the cap and in order to "mold" the cap to a specific head shape, the cap has to be held down manually and fitted before evacuating the air. Once air is evacuated, there is no need for maintaining any additional pressure on the head.

2. The grip of the cap on the head is stronger with larger areas of coverage, small strips of tube balloons were not able to sustain contact on the scalp even under vacuum. More research needs to be done in order to establish the size limitation of maintaining scalp contact for this type of caps. However, balloon caps that are connected together with the square sockets (Figure 5-3) were able to sustain scalp contact.

3. In general, the full head coverage cap shown in Figure 5-5 provided the best stability. Which leads to the conclusion that manufacturing a balloon for a full head cap can potentially provide the best gripping model for a portable NIRS system.

4. The reliance of the vacuum cap on stuffing as part of its mechanism brings back the initial concepts designed for comfort in the previous NIRS cap models presented in Chapter 3 (Figures 3-1 and 3-2). In these models the primary objectives were: to provide a comfortable cap that molds around various head shapes, and to provide an optode engulfing mechanism in order to minimize movement artifacts as well as allow the user to lean or sleep while wearing the cap. Both of these objectives can be met with this design by adjusting the socket in order to engulf the optodes inside the thickness of the cap, as well as adjusting the optode housing to a thinner model.

5. The single consistent concern that remains with the vacuum cap is ventilation, specially for a full head covering cap. The development of a full cap with equally distributed openings at 3 cm intervals may still present a ventilation problem, however, it is possible to design localized patches based on this concept for localized testing, while balloon type solutions can still be studied for an optimized grip on the head.

# CONCLUSION

The work presented in this master thesis identified of the exact role of NIRS caps as an integral part of NIRS imaging systems, especially for future portable applications. The growing importance of this imaging technology is what necessitates a more rigorous look at components that were largely considered as accessories so far.

Materials introduced in this document include theoretical background and extensive literary research that was elaborated in Chapters 1 and 2. The practical applications are presented in Chapter 3 by designing NIRS caps based on traditional and commercially available solutions in addition to hair clearing sockets that were specifically fabricated for the Imaginc group portable NIRS device. An important NIRS cap evaluation method based on the contact pressure it induces on the head and its uniformity was presented in Chapter 4, in addition to the results obtained by testing the working cap models in a comparative study. And finally the introduction of new head-gripping concepts were presented in Chapter 5, for possible future solutions that rely on robotic grippers.

However, any future research into the development of portable NIRS caps has to start by addressing the ideal NIRS imaging cap requirements. These can be summarized in the following points:

1. The cap has to be constructed from non-flexible material in order to ensure optode stability with freely moving subjects.
2. Cap material has to be able to conform with different head shapes.
3. The ability to engulf the optodes can help stabilize them as well as ensure portability overnight.
4. Both concepts of optode stability as well as cap comfort need to be identified by establishing exact pressure values that are associated with optode/scalp contact and stability versus excessive pressure on the head that is associated with cap discomfort.
5. Head ventilation is important in order to protect participants from heat and sweat, specially over long-monitoring periods.

On the other hand, we were able to present important contributions in order to improve portable NIRS systems, these achievement can be summarized as follows:

1. The development of hair clearing socket models that can be employed with any imaging technology in order to decrease the installation time and help bring this technology a step closer towards unassisted, or single person applications.
2. The pressure values associated with stable optode/scalp contact was found to be 30-40 Pa, while the comfort pressure margin on the head was ~50 Pa. These values can help categorize and identify the portability of various NIRS caps based on the amount of pressure they induce on the head.
3. The Introduction of future long-term NIRS cap solutions based on robotic gripper concepts. The two pneumatic solutions proposed for future NIRS caps offer two completely diverse sets of advantages. An electronically sophisticated, sensor based inflating pocket design can be regarded as a step closer towards creating a fully independent brain-device interface using flexible and miniaturized electronic advances, using new signal filtration methods. On the other hand, the vacuum cap solution that is a far simpler model was investigated further and was found to provide several advantages that were identified from the beginning of the project, namely: conformability with various head shapes, and ability to engulf optodes to provide a cap that allows its user to learn or rest while wearing the cap.

However, this work still needs to be followed by various studies in order to successfully achieve its goals. Different aspects of the NIRS cap remains to be addressed and clarified by rigorous testing and by including a large number of participants, namely:

1. The comfort threshold value has to be confirmed by repeating the experiment on a large number of participants. Such a study is underway in collaboration with other members of the Imaginc team (Appendix C).
2. Better vacuum cap manufacturing methods need to be investigated in order to create a better cushioning mechanism. However, since product development processes can be lengthy and may stretch up to several years, it was decided to present this master thesis with the results obtained thus far.

3. The development of hair clearing sockets has to be continued using more flexible polymers. All previously discussed hair clearing sockets are presently being outsourced to be printed with advanced 3D printer technologies that provide the possibility of using different types of material with varying rigidity (Stratasys, 2014).

4. Different studies on tube balloon models are necessary in order to establish the best solutions for a vacuum cap. These studies provide the possibility of creating a NIRS cap that allows for proper head ventilation while providing a good grip on the head. This requires exploration of size and connectivity limitations needed to establish the perfect grip.

5. Sensor based electronically advanced caps can be regarded as a next generation NIRS device development. The incorporation of such a system provides the possibility of addressing for the first time signal filtration based on optode/scalp data that is registered concurrently with the NIRS signal. Particularly with the continued development of flexible electronics and microfabrication techniques that allows for the future incorporation of a micro-valve and a micro-pump within the cap.

6. This study focused mostly on experimental results rather than developing mathematical models and computer generated simulations that may correspond with cap stability and comfort. This was due to two main reasons. Firstly, the study accompanied an actual NIRS device validation process which required several models to be fabricated and used with quick pace and fast results. Secondly, since NIRS cap studies are rare, several key parameters were missing in the identification process of the boundary conditions for any type of theoretical simulations. Such as the necessary pressure induced on the head, the reverse pressure on the cap induced by different hair types, the comfort pressure range and the effect of head shape variations on the pressure based on the type of material. In this study we were able to identify some of these key parameters experimentally, which is an important step towards developing mathematical models that can facilitate future simulations and theoretical models to fulfill NIRS cap requirements. Future NIRS cap studies can provide a much needed theoretical background detailing the forces induced by a NIRS cap and how these forces are distributed and effected with different cap shapes and materials used.

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# APPENDIX A - SAMPLE OF THE QUESTIONNAIRE ACCOMPANYING THE NIRS STUDY AT THE EPIC CENTER

## Questionnaire

**numéro de participant:**

**Renseignements personnels**

| Age | taille de la tête | couleur des cheveux | Type de cheveux |
|---|---|---|---|
| | | | |

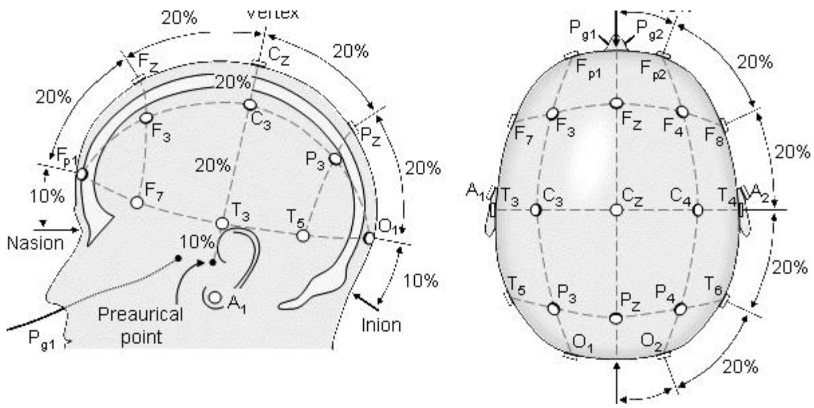
**Plage de confort de la pression:**

**Étape 2:**

**1. Comment qualifieriez-vous le casque que vous avez porté?**

○ **Confortable** ○ **Peu confortable** ○ **inconfortable**

**2. Veuillez indiquer, si c'est le cas, les positions pour lesquelles le casque causait de l'inconfort:**




**3. Veuillez indiquer les types d'inconforts que vous avez ressentis durant la séance:**

| Aucun | Trop serre | Avoir chaud | Tirait les cheveux | Longue installation | Autre |
|---|---|---|---|---|---|
| | | | | | |

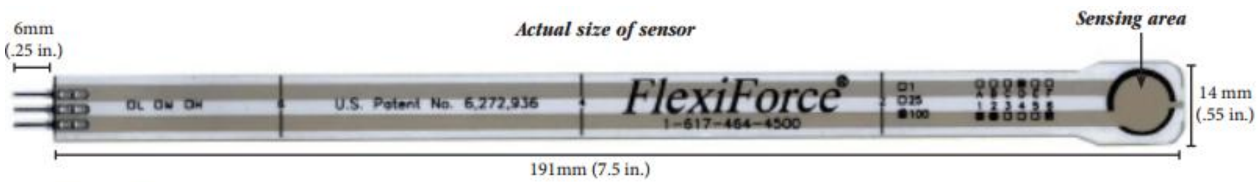
**..........................................................................................................................**

**4. Pendant combien de temps vous sentiriez-vous capable de porter le casque?**

| 1 h | 2 h | 3 h | 4 h | 5 h | 6 h | plus |
|---|---|---|---|---|---|---|
| | | | | | | |

# APPENDIX B - THE CALIBRATION PROCESS OF THE PRESSURE SENSORS

Originally, the sensor circuit connected to the Imaginc 32 Channel system contained four sensors. These sensors were attached to the four legs of a cardboard box. Weight was added inside the box, and it was increased in a uniform fashion by increments of 400g. One of the sensors has proven to be defective, therefore only the data from the three remaining sensors is presented. Each leg was designed to fit the entire sensing area thereby transferring one quarter of the weight placed at equal distances from the four legs to the sensor. Thus a weight of 100 g = 0.98 Newton, corresponds to $0.98/(9.53 \text{ X } 10^{-3}) = 102.8$ Pascal where 9.53 is the total sensing area based on the manufacturers catalogue. Figure B-1 shows the pressure sensor used together with its physical properties.




**Physical Properties**

| | |
|---|---|
| Thickness | 0.203 mm (0.008 in.) |
| Length | 191 mm (7.5 in.)* |
| | *optional trimmed lengths*: 152 mm (6 in.), 102 mm (4 in.), 51 mm (2 in.) |
| Width | 14 mm (0.55 in.) |
| Sensing Area | 9.53 mm (0.375 in.) diameter |
| Connector | 3-pin Male Square Pin (center pin is inactive) |
| Substrate | Polyester (ex: Mylar) |
| Pin Spacing | 2.54 mm (0.1 in.) |

Figure B-1: FlexiForce sensor from Tecksan

Using the known pressure values added in each case, the corresponding voltage values were registered in order to obtain pressure versus voltage sensitivity curve for each sensor.

The sensitivity curve for each sensor is shown in Figures B-2, B-3 and B-4, with the maximum and minimum variations indicated at each value, the logarithmic curve was generated using Excel to fit the experimental results and help provide a better understanding of its linearity. The sensors seem to saturate at values above 700 Pa. However, it is important to note that at lower values the margin of error seems to increase, while the reading seems to stabilize at higher pressure ranges. The pressure sensors were designed and installed by Jerome LeLan as a valuable addition that can be used with the Imaginc group portable NIRS design

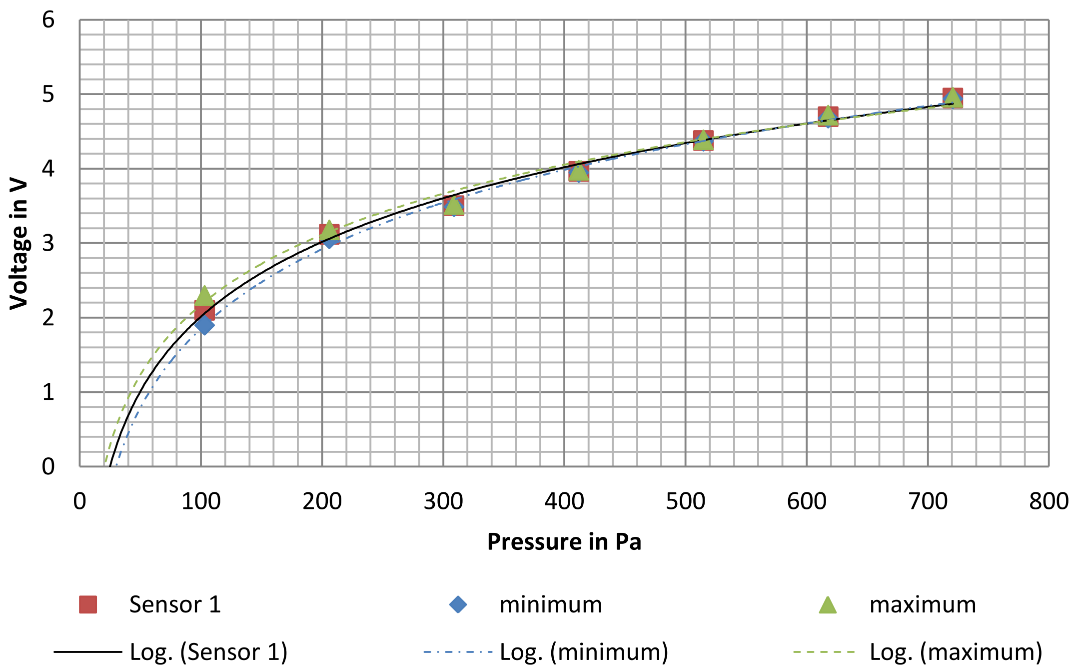



Figure B-2: the sensitivity curve of sensor 1

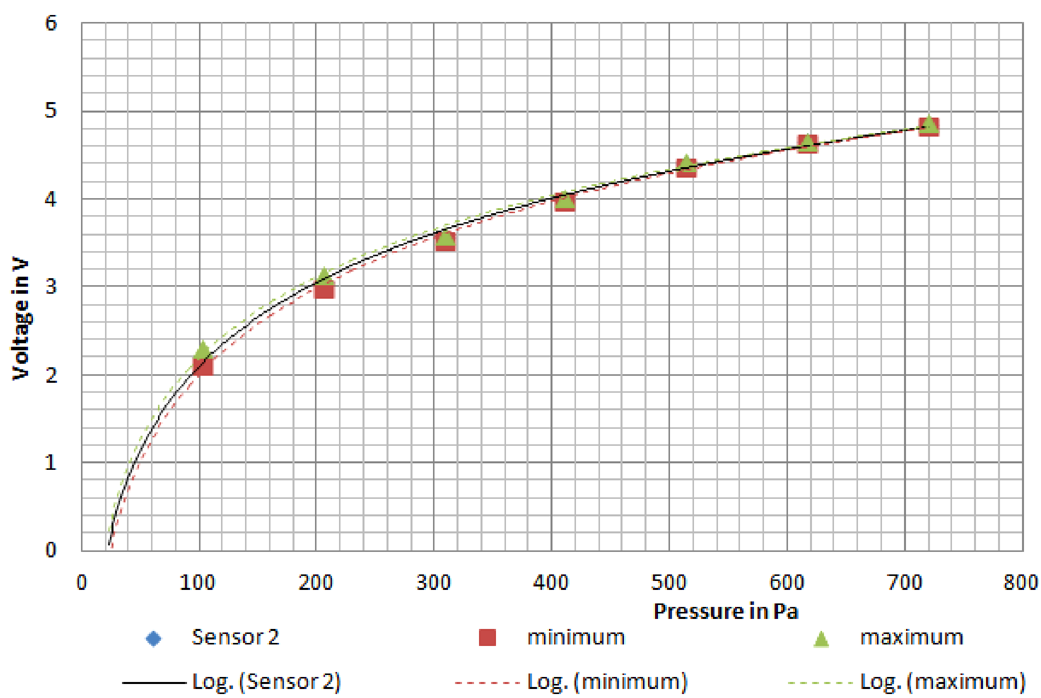



Figure B-3: the sensitivity curve of sensor 2

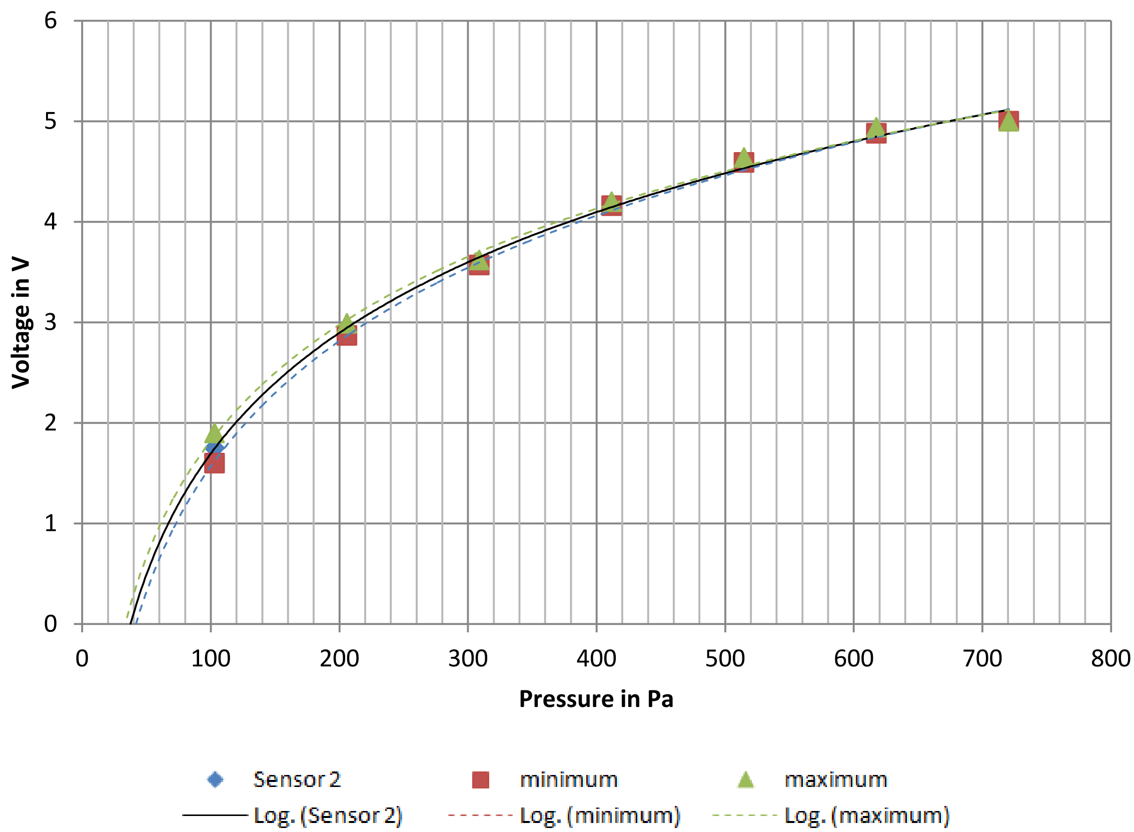



Figure B-4: The sensitivity curve of sensor 3

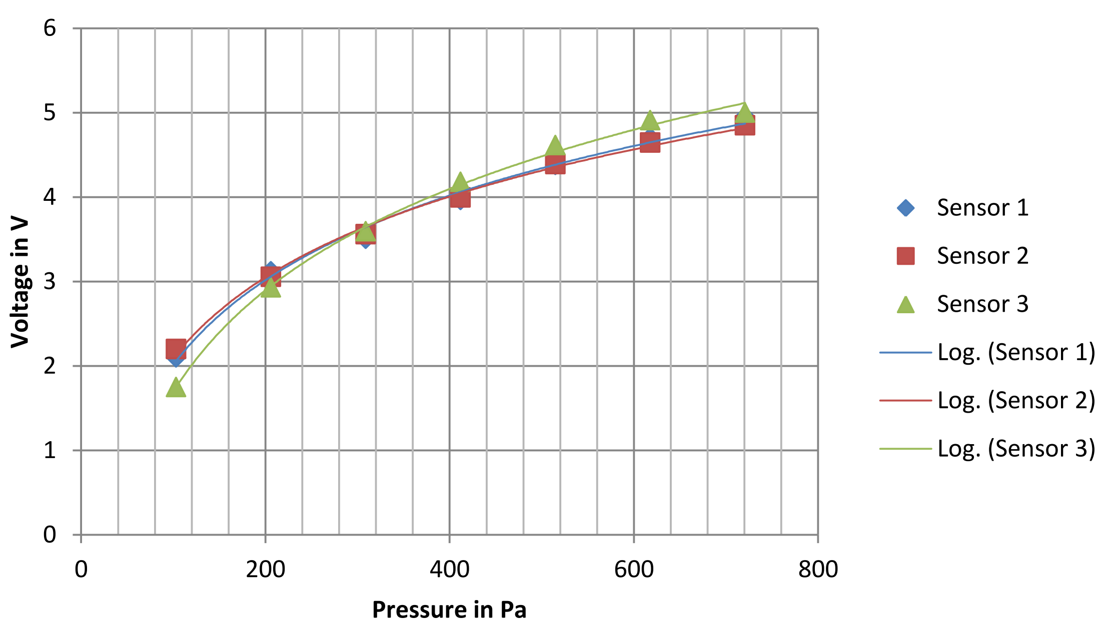



Figure B-5: the sensitivity of the three sensors compared to one another

# APPENDIX C - ETHICS CERTIFICATION FOR A STUDY ON 30 SUBJECT TO ESTABLISH THE COMFORT PRESSURE MARGIN ON THE HEAD

POLYTECHNIQUE MONTRÉAL
LE GÉNIE EN PREMIÈRE CLASSE

**CERTIFICAT D'ACCEPTATION D'UN PROJET DE RECHERCHE PAR LE COMITÉ D'ÉTHIQUE DE LA RECHERCHE AVEC DES ÊTRES HUMAINS DE POLYTECHNIQUE MONTRÉAL**

Le 23 juin 2014

Mme Amal Kassb
M. Mohamad Sawan
Département de génie électrique
Polytechnique Montréal

N/Réf : Dossier CÉR-13/14-22

Madame, Monsieur,

J'ai le plaisir de vous informer que les membres du Comité d'éthique de la recherche ont procédé à l'évaluation en comité restreint de votre projet de recherche intitulé «Casque d'enregistrement de l'activité cérébrale à long terme» et en ont recommandé l'approbation sur la base de la documentation envoyée au CÉR en date du 22 juin 2014.

Veuillez noter que le présent certificat est valable pour une durée de un an, soit du **23 juin 2014 au 22 juin 2015**, pour le projet tel que soumis au Comité d'éthique de la recherche avec des sujets humains.

Nous vous prions de nous faire parvenir un bref **rapport annuel** (http://www.polymtl.ca/recherche/document/deonto.php) afin de renouveler votre certificat au moins un mois avant l'expiration du présent certificat. La secrétaire du Comité d'éthique de la recherche avec des sujets humains devra également être informée de toute modification qui pourrait être apportée ultérieurement au protocole expérimental, de même que de tout problème imprévu pouvant avoir une incidence sur la santé et la sécurité des personnes impliquées dans le projet de recherche (sujets, professionnels de recherche ou chercheurs).

Je vous souhaite bonne chance dans vos travaux de recherche,

Farida Cheriet, présidente
Comité d'éthique de la recherche avec des êtres humains

c.c.: Anne-Marie Bourret, ing., DRI

**Comité d'éthique de la recherche avec des êtres humains**
Pavillon principal
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École Polytechnique de Montréal PROJETS DE RECHERCHE AVEC DES SUJETS HUMAINS

# FORMULAIRE DE DEMANDE DE CERTIFICATION ÉTHIQUE

Transmettre une copie électronique dûment signée de ce document
à la responsable des dossiers d'éthique à la Direction de la recherche et de l'innovation
Annexer, au besoin, tout autre formulaire demandé

| NUMÉRO DE DOSSIER<br>Pour usage interne | CÉR- 13/14-22 |
|---|---|

| | | |
|---|---|---|
| **1. RESPONSABLE DU PROJET**<br>(s'il s'agit d'un **étudiant**, svp cocher : Baccalauréat* ☐ Maîtrise** ☒ Doctorat*** ☐) | | |
| * Si le responsable du projet est un étudiant au **baccalauréat** ou à la **maitrise-cours**, SVP annexer une brève description du projet (incluant ses objectifs, ses hypothèses et une description de la méthodologie utilisée) au présent formulaire.<br>** Si le responsable du projet est un étudiant à la **maîtrise-recherche**, SVP annexer le formulaire « *Approbation du sujet de recherche de maîtrise* » (BAA ET-4) ou le formulaire « *Sujet de recherche et échéancier* » (BAA-ES-ET.02F).<br>*** Si le responsable du projet est un étudiant au **doctorat**, SVP annexer le formulaire « *Sujet de recherche et échéancier* » (BAA-ES-ET.02F) et le « *Rapport du jury de l'examen général de synthèse* » | | |
| NOM :<br>Kassab | PRÉNOM :<br>Amal | TITRE / MATRICULE (étudiant) :<br>1602099 |
| DÉPARTEMENT :<br>Génie biomédical | TÉLÉPHONE :<br>(514) 690 9379<br>COURRIEL :<br>amal.kassab@polymtl.ca | |
| **2. DIRECTEUR DU PROJET** : ☒ Idem au responsable du projet OU voir ci-dessous | | |
| <u>À noter</u> : Le directeur du projet DOIT ÊTRE un professeur ou un chercheur de Polytechnique. S'il s'agit d'un projet réalisé par un étudiant, le directeur du projet doit signer le présent formulaire | | |
| NOM :<br>Sawan | PRÉNOM :<br>Mohamad | TITRE :<br>Professeur |
| DÉPARTEMENT :<br>Génie électrique | TÉLÉPHONE :<br>(514) 340 4711 poste 5943<br>COURRIEL :<br>mohamad.sawan@polymtl.ca | |
| **3. PROJET DE RECHERCHE** | | |
| TITRE du projet : Casque d'enregistrement de l'activité cérébrale à long terme | | |
| Le projet a-t-il déjà été approuvé par le CÉR / CÉRR de POLYTECHNIQUE ? ☐ OUI ☒ NON | | |
| Si oui, numéro de dossier : CÉR- | Date du certificat de conformité : | |
| Le projet a-t-il déjà été approuvé par le CÉR d'un (ou plusieurs) autre(s) établissement(s) ?<br>☐ OUI ☒ NON<br>Si OUI, SVP annexer tout certificat de conformité précédemment émis par un autre CÉR pour le présent projet. | | |
| Si OUI, nom de l'établissement : | Date du certificat : | |

Mohamad Sawan

Signature du responsable de projet Date 20 juin 2014

## 4. COLLABORATEURS INTERNES / EXTERNES AU PROJET

| NOM : | PRÉNOM : | TITRE : |
|---|---|---|
| Lassonde | Maryse | Ph.D. |

| ORGANISME / DÉPARTEMENT : | TÉLÉPHONE : |
|---|---|
| Université de Montréal<br>Département de Psychologie | (514) 343 6959<br>COURRIEL :<br>Maryse.Lassonde@umontrela.ca |

Type de collaboration : Chercheur affilié

| NOM : | PRÉNOM : | TITRE : |
|---|---|---|
| Gallagher | Anne | Ph.D. |

| ORGANISME / DÉPARTEMENT : | TÉLÉPHONE : |
|---|---|
| Université de Montréal<br>Département de Psychologie | 514 345-4931 #6409<br>COURRIEL :<br>anne.gallagher@umontreal.ca |

Type de collaboration : Chercheur affilié

| NOM : | PRÉNOM : | TITRE : |
|---|---|---|
| Nguyen | Dang | Ph.D. |

| ORGANISME / DÉPARTEMENT : | TÉLÉPHONE : |
|---|---|
| Centre hospitalier de l'Université de Montréal (CHUM)<br>Médecine/Neurologie | 514 890.8000 #25070<br>COURRIEL :<br>d.nguyen@umontreal.ca |

Type de collaboration : Chercheur affilié

| NOM : | PRÉNOM : | TITRE : |
|---|---|---|
| Lesage | Frédéric | Professeur |

| ORGANISME / DÉPARTEMENT : | TÉLÉPHONE : |
|---|---|
| Polytechnique Montréal<br>Génie électrique | 514-340-4711 #7542<br>COURRIEL :<br>frederic.lesage@polymtl.ca |

Type de collaboration : Chercheur affilié

## 5. RÉSUMÉ DE LA PROPOSITION DE RECHERCHE

SVP Fournir un résumé d'environ 250 mots, incluant la nature et les objectifs du projet ainsi que les dates prévues de début et de fin du projet. Pour une évaluation en 2 étapes, présenter les renseignements pour chacune des étapes.

Les systèmes spectrospcopy proche infrarouge (SPIR) ont été largement utilisés pour la surveillance de l'activité du cerveau à court terme par apport à fonctions sensorielles et cognitives cérébrales. Alors que la surveillance de l'activité cérébrale à long terme est important pour comprendre la fonctionnalité complexe du cerveau et de surveiller certaines maladies telles que l'épilepsie. Afin d'être en mesure d'accomplir le suivi à long terme, les casque SPIR doivent être stables ainsi que confortable. Malgré que les systèmes commercial offre un certain marge de stabilité, confort n'a pas été étudié, surtout il n'ya pas un plage de pression connue qui est associée avec le confort de la tête. L'objectif de ces expériences est d'identifier les gammes de pression de confort sur la tête dans environ 30 volontaires en bonne santé et de préciser pour la première fois les valeurs de pression induites par les casques SPIR tout au long de la session de l'imagerie.

Afin d'accomplir ceci, le dispositif SPIR portable créer par le group Imaginc était équipé avec quatre capteurs de pression de contact qui fourniront les valeurs dynamiques de pression tout au long de la période d'essai. Ces valeurs seront corrélées avec le confort de bénévole via un questionnaire à la fin de la session de surveillance . En outre, et afin d'identifier la plage de confort de la pression pour chaque participant, un ballon sera utilisé. La pression sur la tête est augmentée de manière incrémentielle afin d'établir le niveau de confort à chaque valeur de la pression en demandant au participant directement, une fois que le participant communique un inconfort définitive à une certaine valeur de pression, l'expérience est conclu.

| **6. MODE DE FINANCEMENT DU PROJET** |
|---|
| ☒ Subvention de recherche<br>(svp indiquer si ☒ la subvention est octroyée ou si ☐ la demande est encore à l'étude)<br>☐ Contrat ou commandite industrielle (contrat signé : ☐ OUI ☒ NON)<br>☒ Autre – préciser : équipe émergente |
| Svp annexer une copie de la demande de subvention ou de la proposition de contrat de recherche.<br>Si le projet n'a pas fait l'objet d'une évaluation scientifique, svp annexer un protocole détaillé avec revue de littérature, hypothèses et/ou objectifs, méthodologie et résultats attendus |
| Organisme subventionnaire (CRSNG, CRSH, IRSC, FQRNT, FRSQ, FQRSC, NIH, IRSST etc.) : IRSC<br>Numéro de référence de la subvention : 62573 |
| Nom du partenaire industriel:<br>Numéro de référence du projet : |

| **7. PARTICIPANTS À LA RECHERCHE** | | |
|---|---|---|
| Critères d'**inclusion**[1] des participants au projet de recherche | | Critères **d'exclusion**[1] des participants au projet de recherche |
| Aucun | | Aucun |
| Caractéristiques des sujets pressentis : étudiants universitaires | | |
| Âge : | 18 ans et plus | Statut : |
| Sexe : | hommes et femmes | Autre : |
| Nombre de participants pressentis : 30 | | |

| **8. RECRUTEMENT DES SUJETS** |
|---|
| 8.1 - À quel endroit les sujets seront-ils recrutés ?<br>À Polytechnique parmi les membres de l'équipe IMAGINC et par annonce. |
| 8.2 - Avez-vous obtenu les autorisations d'accès à ces lieux ? Si oui, SVP annexer les autorisations obtenues<br>Oui, ce sont les locaux normaux des étudiants du professeur Sawan au pavillon Lassonde |
| 8.3 - Quels sont les renseignements divulgués lors du recrutement ? Qui en fait la présentation ? SVP annexer le document concerné.<br>Des explications du fonctionnement du prototype SPIR et des mesures de sécurité (limitation des courants de fuite et des puissances optiques) seront présentées par le responsable du projet à travers le formulaire d'information et de consentement. |
| 8.4 - Des personnes **mineures** ou **inaptes** sont-elles participantes à votre projet de recherche ?<br>☐ OUI ☒ NON<br>Si oui, SVP vérifier la procédure applicable au projet en question. |

[1] Dans le cas où une discrimination serait recherchée pour répondre aux critères du projet de recherche, indiquez les motifs de cette discrimination.

**9. DÉROULEMENT ET MODALITÉS DE LA PARTICIPATION DES SUJETS**

9.1 – SVP décrire ce que les sujets auront à accomplir lors de leur participation au projet de recherche et les interventions pratiquées sur ces sujets.
les participants doivent porter un casque SPIR pour une période de 30 minutes afin de déterminer la pression de contact associé à l'imagerie optique, et la plage de confort de la pression sur la tête

9.2 - À combien de séances les sujets sont-ils tenus de participer ?
1

9.3 - Quelle est la durée de ces séances ?
30 minutes

9.4 - À quel endroit auront lieu ces séances ?
Au local M-5306

9.5 - Une instrumentation quelconque sera-t-elle utilisée dans le cadre de ce projet de recherche ?
☒ OUI ☐ NON
Si oui, SVP décrire l'instrument en question ainsi que ses fonctions et son utilisation. SVP également annexer tous les guides, questionnaires et documents qui seront utilisés lors de cette recherche.

Nous allons utiliser sur les sujets un dispositif de spectromètre proche infrarouge développé par l'équipe du projet. Il s'agit d'un appareil alimenté à batteries (9V), isolé électriquement des installations électriques du bâtiment hôte et communiquant à un ordinateur par un lien optique ou sans fil également isolés électriquement. Des résistances de 100 kΩ sont physiquement ajoutées en série avec les électrodes de l'électroencéphalogramme pour limiter les courants sous le maximum de 100 uA (9 V / 100 kΩ = 90 µA) permis par la norme CEI-60601-1. Même en cas de court-circuit de l'électronique du prototype menant à la situation improbable d'une connexion directe de la batterie sur le sujet humain, le courant sera limité par des résistances ajoutées aux électrodes.

Les optodes seront placées sur la tête, mais elles ne seront pas activées qu'une seule à la fois, le système mesure les valeurs de pression induites par le capuchon et les optodes sur la tête.

9.6 - Comment le chercheur intervient-il lors de la participation des sujets ?
Le chercheur est responsable de l'installation des électrodes et des optodes sur la tête du sujet et du déroulement de l'acquisition des données. Enfin, il retirera les électrodes et optodes du sujet.

9.7 - Les sujets recevront-ils une compensation financière pour cette participation ?
☐ OUI ☒ NON
Si oui, SVP expliquer la nature de cette compensation et les raisons qui la motivent.

9.8 - Avez-vous besoin d'accéder à des données confidentielles concernant le sujet (dossier médical, autres) ?
☐ OUI ☒ NON
Si oui, avez-vous l'autorisation du sujet à cet effet? SVP annexer l'autorisation.

9.9 - Existe-t-il une période de suivi post-recherche ?
☐ OUI ☒ NON
Si oui, SVP décrire le mécanisme de suivi proposé.

**10. AVANTAGES ET INCONVÉNIENTS POUR LES SUJETS**

10.1 - Quels sont les avantages de cette participation pour le sujet ?
Le sujet ne retire aucun avantage personnel à participer à cette recherche. Par contre, il pourrait éprouver de la satisfaction à participer à une recherche qui permet de faire avancer les connaissances

10.2 - Quels sont les inconvénients et les risques de cette participation pour le sujet ? (nature, possibilités, gravité, probabilité - risques prévisibles et imprévisibles, réversibilité des inconvénients et des risques.)
Comme mentionné à la section 9.5, les courants et puissances optiques sont limités selon les normes de sécurité en vigueur. Il n'existe pas de risque connu à l'emploi de ce type de mesures non invasives et les risques encourus par les sujets sont donc négligeables. L'ajustement de l'appareil se fait au niveau du contact entre les optodes et le cuir chevelu du sujet.

10.3 - Les inconvénients et les risques ont-ils été présentés au sujet ?
☒ OUI ☐ NON
Si oui, SVP veuillez annexer le formulaire d'information et de consentement qui sera distribué au sujet.

10.4 - Quelles sont les mesures prévues par le(s) chercheur(s) pour minimiser les inconvénients et les risques ?
La communication verbale et la cessation de l'expérience dès que le sujet présente des signes d'irritation

10.5 - Quels sont les critères envisagés pour suspendre ou arrêter la participation d'un sujet au projet de recherche ?
L'arrêt de la participation d'un sujet au projet de recherche aura lieu si le sujet en fait la demande à tout moment lors de la séance d'enregistrement. Le sujet aura été avisé de la procédure par écrit à travers le formulaire d'information et de consentement, qui consiste essentiellement à demander l'arrêt de l'enregistrement. Au moment où le sujet en fait la demande, la séance d'enregistrement est immédiatement suspendue et le casque retiré du sujet.

**11. CONFIDENTIALITÉ DES PARTICIPANTS**

11.1 - Quels sont les moyens mis en place afin de protéger l'anonymat des participants lors de la recherche ?
Nous assignerons aux fichiers contenant les résultats des expériences des numéros sans lien avec les participants. Par ailleurs, les tracés biométriques de ce type ne permettent pas d'identifier une personne.

11.2 - Quels sont les moyens mis en place afin de protéger l'anonymat des participants lors des publications et des présentations scientifiques ?
Idem

**12. CONFIDENTIALITÉ DES DONNÉES**

12.1 – SVP identifier la personne qui procèdera à la cueillette des données.
Amal Kassab

12.2 - SVP identifier les personnes qui auront accès aux données.
Dr. Sawan, Amal Kassab

12.3 - Quels sont les moyens mis en place pour assurer la confidentialité des données ?
La personne effectuant la collecte des données procédera à l'identification des fichiers par des numéros avant de les distribuer aux autres membres de l'équipe.

12.4 – SVP inventorier les façons de recueillir les données et spécifier le lieu où elles seront conservées.
Les données d'imagerie seront inscrites sur l'ordinateur de l'équipe Imaginc, en plus d'un questionnaire, les deux données seront reliées par le nombre des participants à la place de leur nom.

12.5 - Quelle est la durée de conservation des données avant leur destruction intégrale ?
☒ 10 ans (pour tous les projets de recherche en génie) ☐ 7 ans (pour tous les autres projets)

**PERSONNE RESSOURCE DU PROJET**

SVP identifier une personne ressource, à l'intérieur de l'équipe du projet de recherche, qui est en mesure de répondre aux questions ou aux demandes de renseignements de la part des participants au projet (les sujets) :

Nom : Amal Kassab

Titre : Candidate à la maitrise

Téléphone / courriel : (514) 690 9379 / amal.kassab@polymtl.ca

**INTERVENTION DU DIRECTEUR DU PROJET**

Je soussigné(e) (nom en lettres moulées) Mohamad Sawan accepte de me conformer et de voir à ce que mon étudiant(e) se conforme, le cas échéant, à la politique de l'École Polytechnique sur l'éthique de la recherche avec des êtres humains et aux règles en la matière en vigueur au Canada.

Je m'engage, pour toute la durée du projet, à informer le CÉR de tout changement (méthodologique ou autre) au cours de la réalisation de cette recherche, d'acquiescer aux demandes du CÉR sur ces changements et de m'assurer qu'un court rapport sur le déroulement du projet soit transmis au CÉR annuellement.

Signature du directeur de projet : Mohamad Sawan

Date : 20 juin 2014